TRANSACTIONS

AMERICAN GEOPHYSICAL UNION

VOLUME 32

1951

PUBLISHED BY THE NATIONAL RESEARCH COUNCIL
OF
THE NATIONAL ACADEMY OF SCIENCES
WASHINGTON, D. C.

[See page 149 for "Special Announcements" concerning coming meetings]

TRANSACTIONS
AMERICAN GEOPHYSICAL UNION

Established by the National Research Council of the National Academy of Sciences in 1919

To promote the study of problems concerned with the figure and physics of the Earth, to initiate and coordinate researches which depend upon international and national cooperation, and to provide for their scientific discussion and publication

OFFICERS OF THE UNION

JOHN A. FLEMING, Honorary President

WALTER H. BUCHER, President

F. W. REICHELDERFER, Vice President

K. HILDING BEIJ, General Secretary

WALDO E. SMITH, Executive Secretary
American Geophysical Union
1530 P Street, Northwest,
Washington 5, D. C.

OFFICERS OF THE SECTIONS

Section of Geodesy
HARRY H. HESS, President
ALBERT J. BOSKINSON, Vice President
FRANK L. CULLEY, Secretary

Section of Seismology
PERRY BYERLY, President
LEONARD M. MURPHY, Vice President
JAMES T. WILSON, Secretary

Section of Meteorology
BENJAMIN HOLZMAN, President
HURD C. WILLETT, Vice President
WOODROW C. JACOBS, Secretary

Section of Terrestrial Magnetism and Electricity
J. WALLACE JOYCE, President
VICTOR VACQUIER, Vice President
LEROY R. ALLDREDGE, Secretary

Section of Oceanography
ALFRED C. REDFIELD, President
ROGER R. REVELLE, Vice President
R. H. FLEMING, Secretary

Section of Volcanology
ESPER S. LARSEN, JR., President
THOMAS P. THAYER, Vice President
FELIX CHAYES, Secretary

Section of Hydrology
F. J. VEIHMEYER, President
MERRILL BERNARD, Vice President
RAY K. LINSLEY, Secretary

Section of Tectonophysics
ROBERT BALK, President
FRANCIS BIRCH, Vice President
WILBUR S. BURBANK, Secretary

The Transactions are published bimonthly at 1530 P Street, Northwest, Washington 5, D. C.
Entered as second-class matter August 24, 1945, at the Post Office at Washington, D. C., under Act of August 24, 1912.

EDITORIAL AND PUBLICATION COMMITTEE

K. HILDING BEIJ, Chairman
NORMAN F. BRAATEN (Geodesy)
PHILIP F. CLAPP (Meteorology)
JOHN LYMAN (Oceanography)
H. R. GAULT (Volcanology)
WALTER T. WILSON (Hydrology)
JNO. A. FLEMING (Adviser)
WALDO E. SMITH, Secretary
CHARLES F. RICHTER (Seismology)
DAVID G. KNAPP (Terrestrial Magnetism and Electricity)
W. B. LANGBEIN (Hydrology)
ANNA M. HIETANEN-MAKELA (Tectonophysics)

General notice--The American Geophysical Union welcomes papers and discussions on the various geophysical subjects for publication from members and non-members alike. It reserves the right, however, to reject either papers or discussions in whole or in part and in all cases these are edited by the Editorial and Publication Committee. Manuscripts should be transmitted in triplicate to the American Geophysical Union, 1530 P Street, Northwest, Washington 5, D. C., and also proofs and all correspondence concerning papers.

It is the responsibility of each author to prepare his material in logical and attractive form, so that it may be read by a specialist in the particular field without need of interpolating the author's intention. To this end, a circular entitled "Suggestions to authors on preparation of manuscripts for publication in the Transactions of the American Geophysical Union" has been prepared and will be supplied interested persons upon request. Reports and papers should be concise. Historical summaries of previous results and comments that do not lead to definite conclusions should be brief. The amount of detail included should be governed by the importance of the results and of their interest to geophysicists.

The Transactions include several departments, as follows:

(1) Scientific and technical papers
(2) Discussions of papers under (1)
(3) Progress reports
(4) Letters to Editor
(5) Reviews, Abstracts, Bibliography
(6) Notes, Personalia, Corrigenda
(7) Union, Section, and Committee Activities

All matters for (1) should have a definite scientific or technical interest and should develop aspects of the geophysical sciences. Matter for (2) may be submitted for publication within the limiting date set at the close of each paper. Items of temporary interest will ordinarily not appear in (1) but in (3) or (4).

The American Geophysical Union is not responsible for statements made, or conclusions drawn, by contributors.

Return of copy for illustrations--All illustrative material, including any negatives supplied to, or prepared by, the Union, will be returned to authors if request accompanies manuscript; otherwise such copy will be destroyed upon publication of Transactions in which they are printed.

Reprints--Reprints will be furnished at cost to an author provided order is received when corrected proof is returned. When an order is accompanied by remittance in full, reprints will be sent post or express paid; otherwise cost of forwarding will be added to cost of reprints.

Rates of subscription to non-members

Per annual Volume of six Numbers, in advance	$9.00
Per single current Number	2.00

Available back issues and volumes as per price list to non-members

Communications regarding subscriptions, orders, changes of address, and interest in membership should be sent to the American Geophysical Union, 1530 P Street, Northwest, Washington 5, D. C.

CONTENTS

Transactions, American Geophysical Union Volume 32, Number 1 February 1951

PAPERS

Seismology
On Phenomena Forerunning Earthquakes . . . . . Kenzo Sassa and Eiichi Nishimura 1
Meteorology
Forced Convection Cell Circulation in Clear Air . . . . . Patricia A. Langwell 7
Temperature and Moisture Soundings over the Gulf of Mexico for March, 1949 . . . . . John R. Gerhardt 15
Terrestrial Magnetism and Electricity
Continental Sporadic E Activity . . . . . N. C. Gerson 26
Oceanography
Swash and Swash Mark . . . . . K. O. Emery and J. F. Gale 31
Total Reflection of Surface Waves by Deep Water John D. Isaacs, E. Allan Williams, and Carl Eckart 37
Volcanology
The Adiabatic Gradient in the Mantle . . . . . Jean Verhoogen 41
A Further Investigation of the Radioactivity of the Round Lake and Elzevir Batholiths . . . . . H. A. Slack and K. Whitham 44
Hydrology
A Comparison of Several Heat and Mass Transfer Networks of Interest in Water Conservation . . . . . Heinz F. Poppendiek and Myron Tribus 49
Surface Detention, Rate of Runoff, Land Use, and Erosion Relationships on Small Watersheds . . . . . Leonard Schiff 57
Electrothermic Rig for the Boring of Glaciers . . . . . A. Nixery 68
Stream-Flow Frequency Changes on Coweeta Experimental Watersheds . . . . . J. A. Lieberman and M. D. Hoover 73
Tectonophysics
The Elementary Theory of Subsurface Structural Contouring . . . John W. Harrington 77
Major Shear Fractures of Alaska and Adjacent Regions . . . . . S. S. West 81
On the Origin of the Carolina Bays . . . . . William Schriever 87

PROGRESS REPORTS

General
Report of the Special Committee on the Geophysical and Geological Study of the Continents, 1949-1950 . . . . . G. P. Woollard, Chairman 96
Geodesy
International Cooperation on a Geodetic Project . . . . . Floyd W. Hough 106
Seismology
Report of the Jesuit Seismological Association for 1949 . . . . . J. B. Macelwane and R. R. Heinrich 110
Oceanography
The Institute of Oceanography, University of British Columbia . . . . . G. L. Pickard and W. M. Cameron 112

(Contents concluded over)

DISCUSSION

Geodesy
Atmospheric Refraction at College, Alaska, during the Winter, 1947-1948: Arnold Court, W. D. Lambert and F. W. Darling, and Pierre St. Amand 114

LETTERS TO THE EDITOR

Protons and the Aurora ..... C. W. Gartlein 120
Estimating Bed Load ..... E. W. Lane and W. M. Borland 121
Measurement of Bed-Load Sediment ..... Eugene F. Serr III 123

REVIEWS, ABSTRACTS, AND BIBLIOGRAPHY

Reviews and Abstracts
Garrett Birkoff, Hydrodynamics, S. A. Schaaf 127
Bibliography
Geodesy 127
Seismology 128
Meteorology 129
Terrestrial Magnetism and Electricity 131
Oceanography 132
Volcanology 134
Hydrology 135
Tectonophysics 137

NOTES AND PERSONALIA

Notes 138
Personalia 139

UNION, SECTION, AND COMMITTEE ACTIVITIES

Minutes of Executive Committee Meeting, November 15, 1950
K. Hilding Beij and Waldo E. Smith 141
Appendix 1--Colloquium on Plastic Flow and Deformation within the Earth ..... L. H. Adams 147
Appendix 2--Report of the Committee to Consider the Formation of a Section of Geochemistry and Radioactivity .... Earl Ingerson, Chairman 148
Amendments to the List of Committees of the Union and the Sections 148

SPECIAL ANNOUNCEMENTS

Thirty-Second Annual Meeting, Washington, D. C., April 30-May 2, 1951 149
Ninth General Assembly of International Union of Geodesy and Geophysics 149

Cards of Corporation Members 150

CONTENTS

Transactions, American Geophysical Union Volume 32, Number 2 April 1951

PAPERS

Geodesy
Tidal Variations of Gravity . . . . . M. S. Reford 151
Some Applications of Tensor Analysis to Geodesy . . . . . John A. O'Keefe 157
Harmonic Analysis of Gravity Observations . . . . . Albert J. Hoskinson 163
Seismology
Air-Coupled Flexural Waves in Floating Ice
Frank Press, A. P. Crary, Jack Oliver, and Samuel Katz 166
Elastic Wave Velocities in Sedimentary Rocks. . . . . D. S. Hughes and H. J. Jones 173
Meteorology
A Comparison of Icing Conditions on Mount Washington
with Those Encountered in Flight . . . . . Wallace E. Howell 179
Theory of Surface-Temperature and Heat-Transfer
Oscillations near a Level Ground Surface . . . . . Heinz Lettau 189
Oceanography
The Effect of Wave Steepness on Wave Velocity . . . . . J. R. Morison 201
Some Observations of the Velocity Profile near the Sea Floor . . . . . R. M. Lesser 207
Volcanology
Activity of Parícutin Volcano from January 1 to
June 30, 1950 . . . . . Carl Fries, Jr. and Celedonio Gutiérrez 212
Hydrology
Most Frequent Particle Paths in a Plane . . . . . Hermann von Schelling 222
The Role of Aquifers in Water Supply . . . . . Raphael G. Kazmann 227
A General Formula for Hydrologic Frequency Analysis . . . . . Ven Te Chow 231
Progressive Waves in Non-Artesian Aquifers . . . P. Wilh. Werner and Daniel Norén 238
Variations in Storm Rainfall over Small Areas . . Ray K. Linsley and Max A. Kohler 245
Tectonophysics
The Chemical Potential of a Stressed Solid . . . . . J. Verhoogen 251
The Carupano Area and Its Relation to the Tectonics
of Northeastern Venezuela . . . . . J. C. Maxwell and Gabriel Dengo 259
Research at the Colorado School of Mines in Subjects
Related to the Mechanics of Rock Failure . . . . . Clifton W. Livingston 268

PROGRESS REPORTS

Terrestrial Magnetism and Electricity
Magnetic Work of the United States Coast and Geodetic
Survey from July 1, 1949 to June 30, 1950. . . . . Elliott B. Roberts 279

(Contents concluded over)

Mr. Bernard Luskin
314 E. 56th Street
Brooklyn 3, N. Y.
(abode) '50 A. M.

DISCUSSIONS

Hydrology
Pedological Relations of Infiltration Phenomena: W. C. Rasmussen and W. O. Smith. . 282
Effect of a Partial Cutoff on Seepage Rates:
Don Kirkham, and John S. McNown and En-Yun Hsu 283

REVIEWS, ABSTRACTS, AND BIBLIOGRAPHY

Reviews and Abstracts
Ernest E. Wahlstrom, Theoretical Igneous Petrology, Earl Ingerson 284
Bibliography
General, Geodesy 286
Seismology, Meteorology 287
Terrestrial Magnetism and Electricity 290
Oceanography 292
Volcanology 293
Hydrology 295
Tectonophysics 297

NOTES AND PERSONALIA

Notes 298
Personalia 298

SPECIAL ANNOUNCEMENT

Ninth General Assembly of the International Union of Geodesy and Geophysics, Brussels, Belgium, August 21-September 1, 1951 299

Additions to the Membership, September 11, 1950 to March 10, 1951 300
Cards of Corporation Members 304

CONTENTS

Transactions, American Geophysical Union Volume 32, Number 3 June 1951

THIRTEENTH AWARD OF THE WILLIAM BOWIE MEDAL

Citation . . . . . Richard H. Fleming 337
Presentation . . . . . Walter H. Bucher 339
Response . . . . . Erling Christophersen 339
Acceptance . . . . . Harald U. Sverdrup 339

The William Bowie Medal 340

PAPERS

General
The Application of Electrical Counting to the Compilation of Frequency Distributions and Correlation Tables . . . . . A. R. Kassander, Jr. and D. W. Stebbins 341
Rainfall Frequency: An Aspect of Climatic Variation . . . . . Luna B. Leopold 347
Geodesy
A Gravity Reconnaissance of the Island of Oahu . . . . . George Prior Woollard 358
Tide-Producing Forces and Artesian Pressures William O. George and Frederick E. Romberg 369
Additional Notes on a Semi-Rigorous Method of Adjusting Triangulation Networks . . . . . B. Goussinsky 372
Seismology
PKKP, P'P', and the Earth's Core . . . . . B. Gutenberg 373
Meteorology
On the Energy Balance of the Atmosphere . . . . . Robert M. White 391
Terrestrial Magnetism and Electricity
Magnetic Anomalies at High Altitudes . . . . . Isidore Zietz and Roland G. Henderson 397
Oceanography
Mass Movements in Submarine Canyon Heads . . . . . Francis P. Shepard 405
A Mixing-Length Theory of Tidal Flushing . . . . Arnold B. Arons and Henry Stommel 419
Hydrology
Seepage into Drain Tubes in Stratified Soil: I - Drains in the Surface Stratum; II - Drains below the Surface Stratum . . . . . Don Kirkham 422
Porosity Factor for Case of Laminar Flow through Granular Media . . . . . Joseph B. Franzini 443
An Improved Soil-Moisture Measuring Unit for Hydrologic Studies . . . . . R. E. Youker and F. R. Dreibelbis 447
Nitrate in the Ground Water of Texas . . . William O. George and Warren W. Hastings 450
Tectonophysics
The Structure of the Bed of the Atlantic Ocean . . . . . J. P. Rothé 457
An Example of Re-Intrusion of Serpentine . . . . . Robert G. Thomas 462

(Contents concluded over)

[See page 495 for "Special Announcements"]

Mr. Lloyd E. Brotzman
3811 25th Place, N. E.
Washington 18, D. C.

DISCUSSIONS

Hydrology
Erosion Pavement, Its Formation and Significance: Louis C. Peltier 466
Fluid Resistance of Composite Roughness: Ralph W. Powell, and H. A. Einstein and R. B. Banks 467

LETTER TO THE EDITOR

Hydrology Comes of Age ..... Milton O. Schmidt 470

REVIEWS, ABSTRACTS, AND BIBLIOGRAPHY

Bibliography
General, Geodesy 473
Seismology 474
Meteorology 475
Terrestrial Magnetism and Electricity 477
Oceanography 478
Volcanology, Hydrology 480
Tectonophysics 482

NOTES AND PERSONALIA

Notes (including Corrigenda) 483
Personalia 484

UNION, SECTION, AND COMMITTEE ACTIVITIES

Thirty-Second Annual Meeting (1951)
Minutes, General Assembly
Evening Session 487
Smoker 487
Symposium and Business Meeting 487
Report of the General Secretary 487
Dates of Thirty-Third Annual Meeting 488
Report of the Committee on Resolutions 488
Minutes of the Sections
Appendix A--Geodesy ..... Frank L. Culley 489
Appendix B--Seismology ..... James T. Wilson 490
Appendix C--Meteorology ..... Woodrow C. Jacobs 490
Appendix D--Terrestrial Magnetism and Electricity ..... L. R. Alldredge 491
Appendix E--Oceanography ..... Richard H. Fleming 491
Appendix F--Volcanology ..... Felix Chayes 492
Appendix G--Hydrology ..... R. N. Wilson 493
Appendix H--Tectonophysics ..... W. S. Burbank 494

Twenty-Sixth Meeting (Fresno, California, February 9-10, 1951) 495

SPECIAL ANNOUNCEMENTS

Dates set for Thirty-Third Annual Meeting (May 5-7, 1952) 495
Meeting in Chicago in September 1952 495

Cards of Corporation Members 496

CONTENTS

Transactions, American Geophysical Union Volume 32, Number 4 August 1951

COLLOQUIUM

General
Plastic Flow and Deformation within the Earth (see p. 498 for Contents of Colloquium) . . 497

PAPERS

Geodesy
Radar Altimetry Operations of the United States Geological Survey in 1950 . . . . . Julius L. Speert 544
Meteorology
The Influence of Ground Condition and Cloudiness on the Diurnal March of Surface Vapor Pressure at Blue Hill, Milton, Massachusetts . . . . . Photios P. Karapiperis 547
Surface Ozone at College, Alaska . . . . . W. S. Wilson 552
Terrestrial Magnetism and Electricity
The Representation of the Main Geomagnetic Field and of Its Secular Variation by Means of Two Eccentric Dipoles . . . . . Hans G. Macht 555
Six Additional Years of Spontaneous Increase in Magnetic Moment . . . . . Patrick L. O'Dea and H. Herbert Howe 563
Oceanography
Diurnal Heating of the Surface of the Gulf of Mexico in the Spring of 1942 . . . . . Henry Stommel and Alfred H. Woodcock 565
Volcanology
Activity of Parícutin Volcano from July 1 to December 31, 1950 . . . . . Carl Fries, Jr. and Celedonio Gutiérrez 572
Hydrology
Soil Anisotropy and Some Field Methods for Measuring Permeability . . . . . Ronald C. Reeve and Don Kirkham 582
Parameters for Relating Unit Hydrographs to Watershed Characteristics . . . . . Charles Grant Edson 591
Evaluation of Two Elements Affecting the Characteristics of the Recession Curve . . . . . Carroll F. Merriam 597

REPORT

Geodesy
Geodetic Work Executed in Mexico from April 1949 to March 1950 Manuel Medina Peralta 601

(Contents concluded over)

[See p. 651 for "Special Announcements"]

Mr. Walter T. Wilson
44 Loma Road
Redwood City, California
(or) '38

DISCUSSIONS

Hydrology
Vedernikov's Criterion for Ultra-Rapid Flow: V. V. Vedernikov and Ralph W. Powell 603
Resistance to Flow in Rough Channels: M. W. Owen, J. Th. Thijsse, James F. Halsey, and Ralph W. Powell 607

REVIEWS, ABSTRACTS, AND BIBLIOGRAPHY

Bibliography
General, Geodesy 614
Seismology, Meteorology 615
Terrestrial Magnetism and Electricity 617
Oceanography 619
Volcanology 620
Hydrology 622
Tectonophysics 624

NOTES AND PERSONALIA

Notes (including Corrigenda) 624
Personalia 625

UNION, SECTION, AND COMMITTEE ACTIVITIES

Minutes of the Executive Committee Meeting, May 2, 1951
K. Hilding Beij and Waldo E. Smith 628
Appendix 1--Report of the Committee on Meetings . . John Putnam Marble, Chairman 632
Appendix 2--Report of the Committee on Budget for the Fiscal Year Ending June 30, 1952 . . . . . Herbert N. Eaton, Chairman 632
Appendix 3--Report of the Special Committee on the Geophysical and Geological Study of Continents, 1950-1951. . . . . George P. Woollard, Chairman 634
Appendix 4--Report of the Special Committee on Cosmic-Terrestrial Relationships for the Year Ending June 30, 1951 . . Harlan T. Stetson, Chairman 648

SPECIAL ANNOUNCEMENTS

Thirty-Third Annual Meeting, Washington, D. C., May 5-7, 1952 651
Meeting of the International Union of Geodesy and Geophysics 651

Cards of Corporation Members 652

CONTENTS

Transactions, American Geophysical Union Volume 32, Number 5 October 1951

PAPERS

General

Determination of Flows in Interconnected Estuarine Channels Produced by the Combined Effects of Tidal Fluctuations and Gravity Flows. . . Francis E. Swain 653

Seismology

Propagation of Elastic Waves in a Floating Ice Sheet
Frank Press and Maurice Ewing 673

Terrestrial Magnetism and Electricity

A Photographic Study of Changes of the Infrared Emission of the Polar Aurora . . . . . L. Herman and H. Leinbach 679

Meteorology

On High-Level Cyclones Originating in the Tropics . . . . . C. E. Palmer 683

Free Fall of Drops Through Air . . . . . Walter Hitschfeld 697

On Summertime Rainfall at New York, N. Y. . . . . David K. Todd 701

Oceanography

The Damping Action of Submerged Breakwaters
J. W. Johnson, R. A. Fuchs, and J. R. Morison 704

Graphical Determination of Specific-Volume Anomaly and Current . . E. B. Callaway 719

Volcanology

Terrestrial Heat Flow in Ontario and Quebec
A. D. Misener, L. G. D. Thompson, and R. J. Uffen 729

Hydrology

The Problem of Safe Yield in Insular Ghyben-Herzberg Systems . . . . . Chester K. Wentworth 739

Tectonophysics

A Critique of Geotectonic Elements . . . . . Paul D. Krynine 743

PROGRESS REPORTS

Seismology

Progress Report, Seismological Laboratory, California Institute of Technology, 1950 . . . . . H. Benioff, B. Gutenberg, and C. F. Richter 749

Meteorology

Report of the Standing Committee on Problems of the Upper Atmosphere . . . . . W. W. Kellogg, Chairman, and Others 755

Report of the Committee on Cloud Physics, 1951
Horace R. Byers, Chairman, and Others 760

Report of the Committee on Climatology, 1950-1951
C. W. Thornthwaite, Chairman, and Others 765

Hydrology

Report of Committee on the Chemistry of Natural Waters, 1950-1951. . . . . W. W. Hastings, Chairman 769

(Contents concluded over)

[See page 807 for "Special Announcements" concerning coming meetings]

PROGRESS REPORTS--Concluded

Hydrology--Concluded
Report of the Committee on Ground Water, 1949-1950 S. W. Lohman, Chairman, and Others 769
Appendix 1--Hydrology and Physiography of Limestone Terranes . . . . . A. C. Swinnerton and Others 772

DISCUSSIONS

Meteorology
The Behavior of Water Drops at Terminal Velocity in Air: James E. McDonald and Duncan C. Blanchard 775
Oceanography
Forces Exerted by Waves on a Sloping Board: John H. Carr and W. S. Hamilton 777
Hydrology
Numerical Solutions for Tile Drainage of Layered Soils: Abdel-Aziz I. Kashef, and James N. Luthin and R. E. Gaskell 779
Rainfall, Infiltration, and Hydraulics of Flow in Runoff Computation: Leonard Schiff, and H. N. Holtan and M. H. Kirkpatrick, Jr. 780

LETTER TO THE EDITOR

Graduate Instruction in Geodetic Engineering . . . . . Milton O. Schmidt 783

UNION, SECTION, AND COMMITTEE ACTIVITIES

Informal Report on the Ninth General Assembly of the International Union of Geodesy and Geophysics Held in Brussels, Belgium, August 21 to September 1, 1951 . . . . . Waldo E. Smith 785

REVIEWS, ABSTRACTS, AND BIBLIOGRAPHY

Bibliography
General, Geodesy 789
Meteorology 790
Terrestrial Magnetism and Electricity 792
Oceanography 796
Volcanology 797
Hydrology 798
Tectonophysics 799

NOTES AND PERSONALIA

Notes 799
Personalia 800

Additions to the Membership, March 11 to September 10, 1951 802

SPECIAL ANNOUNCEMENTS

Thirty-Third Annual Meeting, Washington, D. C., May 5-7, 1952 . . . John Putnam Marble 807
Twenty-Seventh Regional Meeting to be held in Pasadena, California, February 8-9, 1952 . 807

Cards of Corporation Members 808

CONTENTS

Transactions, American Geophysical Union Volume 32, Number 6 December 1951

PAPERS

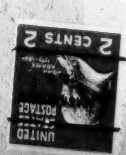
Geodesy
A Discussion of the Accuracy Required in Astronomic Determinations for Laplace Azimuth Control . . . . . Warren D. Forrester 809
New Determinations of the Velocity of Radio Waves . . . . . Carl I. Aslakson 813
Seismology
Rayleigh Waves from Small Explosions M. B. Dobrin, R. F. Simon, and P. L. Lawrence 822
Meteorology
Instrumentation for Recording Microclimatological Factors . . . . . F. A. Brooks and C. F. Kelly 833
Discussion . . . . . Herbert B. Schultz 846
A Kinematic Relationship in the Field of Motion in Storms . . . . . Leon Sherman 849
Analyzing Turbulence by Means of Photographs of Airborne Particles . . . . . Albert V. Hardy 853
Terrestrial Magnetism and Electricity
The Variation of the Geomagnetic-Activity Recurrence Interval with the Solar Cycle . . . . . Edwin J. Chernosky 861
Oceanography
The Relationship between Sand Size and Beach-Face Slope . . . . . Willard N. Bascom 866
Wave Measurements at the Columbia River Light Vessel, 1933-1936 . . . . . Morrough P. O'Brien 875
Correlation of Heights of Observed and Computed Deep-Water Wind Waves in North Atlantic Ocean and Mediterranean Sea . . . . . Frank MacDougal 878
Volcanology
Carbon Content and Radioactivity of Marine Rocks . . . . . Virginia L. Burton and Geraldine R. Sullivan 881
Hydrology
An Electrical Analogue for the Study of Diffusion Processes with Internal Gains or Losses . . . . . C. H. M. van Bavel and A. W. Waltner 885
Evaluation of the Critical Regime in Stratified Flow . . . . . A. Craya 891
On the Origin of River Meanders . . . . . P. Wilh. Werner 898
Interception of Rain and Snow by Second-Growth Ponderosa Pine . . . . . P. B. Rowe and T. M. Hendrix 903
Turbulence Flume to Measure Bed Load . . . . . Maurice L. Albertson 909
Tectonophysics
The Use of Modified Orthographic Projections in Structural Geology . . . . . V. G. Gabriel and Miltón A. Sobie 912

(Contents concluded over)

[See page 954 for "Special Announcements" concerning coming meetings]

3193 G

Dr. J. W. Joyce
6641-32nd Street, N. W.
Washington, 15, D.C.
(bdh) '54



PROGRESS REPORT

Hydrology
Report of the Committee on Infiltration, 1950-1951
L. L. Harrold, Chairman, and Others 919

TECHNICAL NOTES

Hydrology
An Improved Sand Classifier . . . . . H. L. Uppal and Gajinder Singh 923
A Method for Comparing the Flow from a Pair of Experimental Watersheds . . . . . B. C. Goodell 927

DISCUSSIONS

Hydrology
A Comparison of Several Heat and Mass Transfer Networks of Interest in Water Conservation: Ernest R. Anderson, J. J. Marciano and G. E. Harbeck, Jr., and H. F. Poppendiek and M. Tribus 931
Variations in Storm Rainfall over Small Areas: Walter T. Wilson, and Ray K. Linsley and Max A. Kohler 932

UNION, SECTION, AND COMMITTEE ACTIVITIES

Minutes of the Executive Committee Meeting, October 15, 1951
K. Hilding Beij and Waldo E. Smith 934
Appendix 1--Report of the Committee on Audit . . . . . R. H. Weightman, Chairman 938

REVIEWS, ABSTRACTS, AND BIBLIOGRAPHY

Bibliography
Geodesy 941
Seismology 942
Meteorology 943
Terrestrial Magnetism and Electricity 945
Oceanography, Volcanology 947
Hydrology 949
Tectonophysics 950

NOTES AND PERSONALIA

Notes 952
Personalia 952

SPECIAL ANNOUNCEMENTS

Meeting in Pasadena, California, February 8-9, 1952 954
Thirty-Third Annual Meeting, Washington, D. C., May 5-7, 1952 954
Meeting in Chicago, September 11-12, 1952 954
Index to back Transactions available 954

Cards of Corporation Members 955

INDEX, VOLUME 32--1951

Index of Names 956
Index of Subjects 958

INDEX TO VOLUME 32--1951

INDEX OF NAMES

[a]Indicates obituary

Aarons, J., 308, 321
Ackermann, W. C., 310
Adams, L. H., 147, 307, 316, 499
Ahrens, L. H., 306, 314
Albertson, M. L., 310, 909
Alldredge, L. R., 491
Anderson, Ernest R., 931
Anderson, J. L., 311, 335
Arnold, G. L., 308, 318
Arons, Arnold B., 419
Aslakson, Carl I., 813
Averill[a], Charles Volney, 953
Ayers, J. C., 309, 324

Baker, L. S., 309, 321
Bakhmeteff[a], Boris A., 801
Banks, R. B., 467
Banks, R. E., 309, 323
Bascom, W. N., 309, 324, 866
Beij, K. Hilding, 141, 628, 934
Benioff, Hugo, 508, 749
Bennett[a], Charles Stuart, 953
Bernard[a], Merrill, 626
Bijlaard, P. P., 518, 526, 535
Birch, Francis, 533
Birkoff, Garrett, 127
Bjerknes[a], Vilhelm F., 485
Black, R. F., 310, 330
Blair[a], Thomas Arthur, 140
Blanchard, Duncan C., 775
Blaney, H. F., 311, 332
Bodman, G. B., 310
Borland, W. M., 121
Bowie, William, 337
Bowser, C. W., 311, 333
Boyd, F. R., 310, 327
Brooks, F. A., 833
Bucher, Walter H., 339, 514
Bullard, E. C., 520, 525, 538
Bumpus, D. F., 309, 324
Burbank, W. S., 494
Burgers, J. M., 500, 520
Burgess[a], Laurie Reid, 953
Burnight, T. R., 308, 320
Burton, Virginia L., 881
Byers, Horace R., 760
Byrnes, B. C., 309, 321

Cain, J. C., 308, 319
Callaghan, E. C., 310
Callaway, E. B., 719
Cameron, W. M., 112
Carr[a], George W., 486
Carr, John H., 777
Chayes, Felix, 492
Chernosky, E. J., 309, 322, 861
Chow, Ven Te, 231
Christophersen, Erling, 339
Clapp, P. F., 308, 319
Cloos, E., 311
Collins[a], Harry L., 486
Court, Arnold, 114
Cox, J. F., 536
Cramer, S. R., 311, 333
Crary, A. P., 166, 307, 316
Craya, A., 310, 329, 891
Croft, A. R., 310, 311
Culley, Frank L., 489

Darling, F. W., 114
Dehlinger, P., 307, 317
Dengo, Gabriel, 259
Dobrin, M. B., 307, 317, 822
Dodd, P. H., 310, 328
Donley, D. E., 310
Donn, W. L., 307, 315
Dreibelbis, F. R., 447

Eaton, Herbert N., 632
Eckart, Carl, 37
Edson, Charles Grant, 591
Einstein, H. A., 467
Emery, K. O., 31
Ewing, M., 307, 314, 673

Field, W. O., 310, 331
Fisher, J. E., 310, 331
Fleming, Richard H., 337, 491
Forrester, W. D., 307, 314, 809
Franzini, Joseph B., 443
French[a], Owen Bert, 486
Fries, Carl, Jr., 212, 572
Fuchs, R. A., 704

Gabriel, V. G., 912
Gale, J. F., 31
Gane, P. G., 307, 317
Garland, G. D., 307, 314
Garrels, R. M., 310, 328
Garstka, W. U., 310
Gartlein, C. W., 120
Gaskell, R. E., 779
Gebhardt, R. E., 309, 322
George[a], Milton C., 627
George, Wm. O., 369, 450
Gerhardt, John R., 15
Gerson, N. C., 26
Glangeaud, M. L., 521
Gleeson, T. A., 308, 319
Goguel, Jean, 504, 520, 526
Golomshtok[a], Eugene A., 627
Goodell, B. C., 311, 331, 927
Goussinsky, B., 372
Graham, J. W., 311, 336
Graham[a], Robert A., 627
Greenstone, R., 308, 321
Griggs, David, 505, 525, 526, 527
Guenther, W. G., 308, 319
Gumbel, E. J., 310, 330
Gutenberg, B., 373, 525, 539, 749
Gutiérrez, Celedonio, 212, 572

Halsey, James F., 607
Hamilton, W. S., 777
Hantush, M. S., 310, 330
Harbeck, G. E., Jr., 931
Hardy, Albert V., 853
Harrington, John W., 77
Harrold, L. L., 310, 919
Hastings, W. W., 310, 450, 769
Havens, R. J., 308, 320
Hawes[a], Norman E., 140
Hazard[a], Daniel Lyman, 953
Heinrich, E. Wm., 310, 328
Heinrich, R. R., 110
Heiskanen, W., 307, 314, 524, 525
Henderson, Roland G., 397
Hendrix, T. M., 903
Herman, Louis, 308, 320, 679
Herman, Renee, 308, 320
Herrmann, Leo A., 311, 334
Hess, H. H., 528
Hess, S. L., 308, 319
Hinckley, T. J., 309, 322
Hitschfeld, W., 308, 318, 697
Holtan, H. N., 780
Hoover, M. D., 73
Hoskinson, Albert J., 163
Hough, Floyd W., 106
Hough, J. L., 311
Howe, H. H., 309, 322, 563
Howell, Wallace E., 179
Hsu, En-Yu, 283
Huff, F. A., 310, 330
Hughes, D. S., 173
Hulburt, E. O., 308, 320
Hurley, P. M., 306, 308, 313, 320
Hussein[a], Abd Essalam M., 627

Ingerson, Earl, 148, 284
Isaacs, John D., 37
Ives, R. L., 308, 318
Izzard, C. F., 311

Jacob, C. E., 310, 330
Jacobs, Woodrow C., 490
James, Richard, 309, 325
Jardetsky, W. S., 311, 335
Johnson, J. W., 309, 310, 704
Johnson, M. H., 308, 320
Johnston, H. F., 309

Jones, C. L., 310, 328
Jones, H. J., 173
Kaplan, L. D., 308, 319
Karapiperis, Photios P., 547
Kashef, Abdel-Aziz I., 779
Kassander, A. R., Jr., 341
Katz, Samuel, 166, 307, 316
Kazmann, Raphael G., 227
Keller, F., Jr., 309, 321
Kellogg, W. W., 755
Kelly, C. F., 833
Kennedy, G. C., 310, 327
Kirkham, Don, 283, 422, 582
Kirkpatrick, M. H., Jr., 780
Knapp, D. G., 309, 322
Knappen[a], T. T., 486
Kohler, Max A., 245, 932
Koogler, J. T., 311, 332
Kooman, M. J., 308, 320
Krick, I. P., 310
Krynine, Paul D., 743
Kulp, J. L., 306, 313

Lambert, W. D., 114
Lane, E. W., 121
Langwell, Patricia A., 7, 308, 318
Lawrence, P. L., 307, 317, 822
Leinbach, H., 679
Leipper, D. F., 309, 324
Leopold, Luna B., 347
Lesser, R. M., 207
Lettau, Heinz, 189
Lieberman, J. A., 73
Linsley, Ray K., 245, 932
Livingston, Clifton W., 268
Lohman, S. W., 769
Long, R. W., 309, 322
Longard, J. R., 309, 323
Lowrey, R. D., 308, 319
Luthin, James N., 779
Lynch, J., 307, 316

MacDougal, Frank, 309, 325, 878
Macelwane, J. B., 110
Macht, Hans G., 555
Malkus, J. S., 308, 319
Marble, J. P., 306, 632, 807
Marciano, J. J., 931
Marshall[a], Patrick, 486
Maxwell, J. C., 259
McCall, J. S., 307
McCrady, E., 306, 313
McDonald, James E., 775
McDonald[a], Stanley M., 299
McNown, John S., 283
Medina Peralta, Manuel, 307, 314, 601
Merriam, Carroll F., 597
Miller, A. R., 309, 323
Misener, A. D., 729
Moore, R. C., 306, 313
Morison, J. R., 201, 309, 704

Nadai, A., 311, 335, 504
Nelson, M. G., 310
Nishimura, Eiichi, 1
Nizery, A., 66
Norén, Daniel, 238

O'Brien, Morrough P., 875
O'Dea, P. L., 309, 322, 563
O'Donnell, G., 308
O'Halloran, D. J., 307, 315
O'Keefe, John A., 157, 307
Oliver, Jack, 166, 306, 316
Owen, M. W., 607

Packer, D. M., 308, 320
Palmer, C. E., 683
Peltier, Louis C., 466
Petersen[a], Wm. F., 140
Peterson, H. V., 310
Pickard, G. L., 112
Pierson, W. J., Jr., 309, 325
Plummer[a], Helen Jeanne, 486
Poland, J. F., 311
Poppendiek, Heinz F., 49, 931
Powell, Ralph W., 467, 603, 607
Press, F., 166, 307, 316, 673
Price, W. A., 309, 323
Puertas, C. G., 309, 323

Rappleye, H. S., 307, 315
Rasmussen, W. C., 282
Rauch, S. E., 309, 325
Redfield, A. C., 309, 324
Reeve, Ronald C., 582
Reford, M. S., 151
Richter, C. F., 749
Roberts, E. B., 279, 309, 322
Roberts, F. H. H., Jr., 306, 313
Robinson, T. W., 311, 333
Romberg, Fred E., 369
Rothé, J. P., 457
Rowe, P. B., 903

St. Amand, Pierre, 114
Sassa, Kenzo, 1
Schaaf, S. A., 127
Schell, I. I., 309, 324
Schiff, Leonard, 57, 780
Schmidt, Milton O., 470, 783
Schriever, William, 87
Schultz, Herbert B., 846
Schwarz, H. E., 311, 332
Scolnik, R., 308, 320
Seiwell[a], Harry Richard, 299
Serr, Eugene F., III, 123
Shepard, Francis P., 405
Sherman, Leon, 849
Shrikant[a], Ranbir Singh, 299
Simon, R. F., 307, 317, 822
Singh, Gajinder, 923
Skibitzke, H. E., 311, 332
Skillman, T. L., 309, 322
Slack, H. A., 44
Smith, W. O., 282
Smith, Waldo E., 141, 628 785, 934
Snoddy[a], Leland Bradley, 140
Sobie, Milton A., 912
Speert, J. L., 307, 314, 544
Spreen, W. C., 308, 318
Sprengnether[a], W. F., Jr., 953
Stebbins, D. W., 341
Stern, M. E., 308, 319
Stetson, Harlan T., 648
Stommel, Henry, 419, 565
Stout, G. E., 310, 330
Sullivan, Geraldine R., 881
Sverdrup, Harald U., 339
Swain, Francis E., 310, 329, 653
Swingle, D. M., 308, 321
Swinnerton, A. C., 772

Tatel, H. E., 307, 316
Taylor, A. B., 311, 332
Thijsse, J. Th., 607
Thomas, C. W., 309, 323
Thomas, Robert G., 462
Thompson, L. G. D., 729
Thornthwaite, C. W., 765
Todd, David K., 701
Torreson, O. W., 311, 336
Tribus, Myron, 49, 931
Turner, S. F., 311, 332
Tuve, M. A., 307, 316

Uffen, R. J., 729
Umbgrove, J. H. F., 535
Upham, S. H , 309, 324
Uppal, H. L., 923

van Bavel, C. H. M., 310, 331, 885
Vedernikov, V. V., 603
Vening Meinesz, F. A., 523, 531
Verhoogen, Jean, 41, 257, 310, 328
Vestine, E. H., 537
von Arx, W. S., 309, 324
von Schelling, Hermann, 222, 310, 329

Wahlstrom, Ernest E., 284
Waltner, A. W., 310, 331, 885
Weightman, R. H., 898
Weiss, L. L., 308, 318
Weiss, O., 309, 321
Wells, H. W., 308, 320
Wentworth, Chester K., 739
Werner, Harry J., 311, 333
Werner, P. Wilh., 238, 898
West, S. S., 81
White, Robert M., 391
Whitham, K., 44
Wilcox, R. E., 310, 327
Williams, E. Allan, 37
Williams, H., 310, 326
Wilm, H. G., 310
Wilson, J. Tuzo, 311, 335
Wilson, James T., 490
Wilson, R. N., 494
Wilson, W. S., 308, 319, 552
Wilson, Walter T., 932
Woodcock, Alfred H., 565
Woollard, G. P., 96, 307, 315, 358, 634

Work, R. A., 310
Worzel, J. L., 307, 314
Wyatt, W. H., 308, 318
Yoder, H. S., 310, 327
Yogi, K., 310, 326
Youker, R. E., 447
Zies, E. G., 310, 325
Zietz, Isidore, 397

INDEX OF SUBJECTS

Abstracts and reviews, 127, 284, 313-336
Adiabatic gradient in the mantle, 41
Age work at Lamont Geological Observatory, 313
Air, clear, forced convection cell circulation, 7
Airborne magnetic operations, 321
Airborne particles for analyzing turbulence, 853
Air-coupled flexural waves in floating ice, 166
Airflow over a heated island, 319
Alaska, shear fractures, 81
Alaska, College, atmospheric refraction, 114
Alaska, College, surface ozone, 319, 552
Alaska, glacier variation in Glacier Bay, 331
Alpha activity in zircon and sphene, 313
Analogue, electrical, for study of diffusion processes, 331, 885
Anomalies, magnetic, at high altitudes, 397
Antarctic circumpolar current, 323
Aquifer, leaky, non-steady Green's function, 330
Aquifers, non-artesian, progressive waves, 238
Aquifers, role in water supply, 227
Archeology and carbon 14 dates, 313
Arctic inversion, daily fluctuation, 318
Arctic Ocean, physical and biological investigations, 323
Arizona, use of water by phreatophytes, 332
Artesian pressures and tide-producing forces, 369
Assembly, Ninth General, International Union of Geodesy and Geophysics, 149, 299, 651, 785
Astronomic determination for Laplace azimuth control, 314, 809
Atlantic Ocean, observed and computed deep-water wind waves, 325, 878
Atlantic Ocean, structure of bed, 457
Atlantis, problem of, 335
Atmosphere, energy balance, 391
Atmosphere, upper, soft X-ray intensities, 320
Atmospheric pressure and density to 160 km, 320
Atmospheric refraction at College, Alaska, 114
Audit, committee report, 938
Aurora and protons, 120
Aurora, polar, infrared emission, 679
Aurora spectrum, new band systems of nitrogen, 320
Azimuth control (Laplace), accuracy in astronomic determinations, 314, 809

Beach width, water temperature, wave steepness at Carmel, California, 324
Beach-face slope and sand size, 866
Bed load, estimating, 121
Bed load, measurement by turbulence flume, 909
Bed-load sediment, measurement of, 123
Bering Sea, physical and biological investigations, 323
Bibliography
  General, 286, 473, 614, 789
  Geodesy, 127, 286, 473, 614, 789, 941
  Hydrology, 135, 295, 480, 622, 798, 949
  Meteorology, 129, 287, 475, 615, 790, 943
  Oceanography, 132, 292, 478, 619, 796, 947
  Seismology, 128, 287, 474, 615, 942
  Tectonophysics, 137, 297, 482, 624, 799, 950
  Terrestrial magnetism and electricity, 131, 290, 477, 617, 792, 945
  Volcanology, 134, 293, 480, 620, 797, 947
Boring glaciers, electrothermic rig for, 66
Bowie Medal, Thirteenth Award, 337
Breakwaters, submerged, damping action, 704
Brightness of the twilight sky, 320
British Columbia, University of, Institute of Oceanography, 112
Budget, committee report, 632

Calcium method, feasibility in age determinations, 314
California, earthquakes, shear-wave vibrational directions, and related fault movements, 317
California Institute of Technology, Seismological Laboratory, progress report, 749
Canada, gravity measurements, Maritime Provinces, 314
Canada, radioactivity of Round Lake and Elzevir Batholiths, 44
Canada, terrestrial heat flow in Ontario and Quebec, 729
Carbon content and radioactivity of marine rocks, 881
Carbon 14 dates and archeology, 313
Carolina Bays, origin of, 87
Carupano area, Venezuela, relation to tectonics, 259
Chemical potential of a stressed solid, 251
Chemical segregation and heat flow of the mantle, 328
Chemistry of natural waters, committee report, 769
Circulation, effect on distribution of temperature, 319
Circulation, general, and kinematic vortex theory, 319
Climatic variation and rainfall frequency, 347
Climatology, committee report, 765
Cloud cover and height, 318
Cloud physics, committee report, 760
Cloudiness and ground condition, influence on vapor pressure, 547
Coast and Geodetic Survey, magnetic work, 279
Cold-front passages, microseismic study, 315
Colloquium on plastic flow and deformation within the Earth, 147, 497
Colorado School of Mines, research in mechanics of rock failure, 268

Columbia River light vessel, wave measurements, 875
Committees of Union and Sections, amendments to list, 148
Continents, committee report, 96
Contraction hypothesis, and geophysical and geological observations, 335
Control and eradication of phreatophytes, 333
Convection cell, forced, circulation in clear air, 7
Convection-current hypotheses of mountain building, 527
Convection currents and the mantle, 531, 533
Convection currents in the Earth, 535
Corporation members, cards, 150, 304, 496, 652, 808, 955
Correlation tables and frequency distributions, electrical, 341
Cosmic-terrestrial relationships, committee report, 648
Critical regime in stratified flow, 329, 891
Crustal strain characteristics from earthquake sequences, 508
Crustal structures indicated by explosion waves, 316
Crystallization and rock textures, 328
Cumulus, onset of rain, 318
Current and specific-volume anomaly, graphical determination, 719
Current, Antarctic circumpolar, dynamics of, 323
Cyclones, high level, originating in the tropics, 683

Damping action of submerged breakwaters, 704
Davis Strait and Baffin Bay icebergs, estimate of berg count off Newfoundland, 324
Deformation, inelastic, of material, 500
Deformation of Earth's crust, 520, 523
Deformation of materials under stress, 500
Deformation of rocks, mechanical questions, 504
Detention, runoff, land use, and erosion relationships on small watersheds, 57
Diffusion processes with internal gains or losses, electrical analogue, 331, 885
Dipoles, eccentric, to represent main geomagnetic field and its variation, 555
Distribution, circular normal, 330
Drain tubes in stratified soil, seepage into, 422
Drainage of layered soils, numerical solutions, 779
Drops of water at terminal velocity in air, 775
Drops, free fall through air, 318, 697

Earth, hypothesis of convection currents, 535
Earth, plastic flow and deformation, 499
Earth, stress and strain in the outer solid shell, 335
Earthquake sequences and crustal strain, 508
Earthquakes, on phenomena forerunning, 1
Earth's core and PKKP, P'P', 373
Earth's core, temperature at boundary, 328
Earth's crust, deformation, 520, 523
Earth's interior, fluid motion inferred from geomagnetism, 537
Elastic waves in a floating ice sheet, 673
Electric and magnetic fields about a rocket, 320
Electrical counting, application to frequency distributions and correlation tables, 341
Energy balance of the atmosphere, 391
Erosion pavement, formation and significance, 466
Erosion, relationships to detention, runoff, land use, 57
Eruption of Volcano Coseguina, Nicaragua, 326
Estuarine channels, interconnected, determination of flows, 329, 653
Evapotranspiration by phreatophytes from climatological data, 332
Exchange, fresh-water, in Great South Bay, Long Island, 324
Executive Committee meeting, minutes of, 141, 628, 934
Explosions, small, Rayleigh waves from, 822
Extrusion and magma production, volume change, 327

Fennoscandia, postglacial uplift of land, 524
Fennoscandian pegmatites, structural features, 328
Flow from pair of experimental watersheds, comparison, 331, 927
Flow resistance in rough channels, 607
Flows in interconnected estuarine channels, 329, 653
Fluid resistance of composite roughness, 467
Folded belts and geosynclines, formation of, 514
Frequency changes in stream flow on Coweeta Experimental Watershed, 73
Frequency distributions and correlation tables, application of electrical counting, 347

General
  Bibliography, 286, 473, 614, 789
  Colloquium, 499
  Papers, 341, 347, 653
  Progress report, 96, 634, 648
Geochemistry and radioactivity, committee report, consideration of formation of Section, 148
Geodesy
  Abstracts, 314
  Applications of tensor analysis, 157
  Bibliography, 127, 286, 473, 614, 789, 941
  Discussion, 114
  Geophysical, 314
  Minutes of Section, 489
  Papers, 151, 157, 163, 358, 369, 372, 544, 809, 813
  Progress report, 106, 601
Geodetic engineering, graduate instruction, 783
Geodetic project, international cooperation on, 106
Geodetic work in Mexico, 314, 601
Geologic time, symposium on measurement of, 313
Geological Survey, U. S., radar altimetry operations, 1950, 314, 544
Geomagnetic-activity recurrence interval, 322, 861
Geomagnetic field and secular variation, representation by two eccentric dipoles, 555
Geomagnetic work, punch-card processing, 322

Geomagnetism in study of fluid motion of Earth's interior, 537
Geomagnetism, reversible susceptibility and the induction factor, 322
Geophysical and geological observations, explanation by contraction hypothesis, 335
Geophysical and geological study of continents, committee report, 96, 634
Geophysical geodesy, 314
Georgia, structural geology and petrology of Stone Mountain - Lithonia district, 334
Geosynclines and folded belts, formation, 514
Geosynclines, deformation of the Earth's crust in, 523
Geosynclines, mountain formation and volcanism, 518
Geotectonic elements, critique, 743
Ghyben-Herzberg systems, insular, safe yield, 739
Glaciation, control of cycles by changes in flow of internal heat of Earth, 331
Glacier variations in Glacier Bay, Alaska, 331
Glaciers, electrothermic rig for boring, 66
Gravimeter, world network, 315
Gravity anomalies and postglacial uplift, 524
Gravity-anomaly fields, positive and negative, 525
Gravity measurements at sea, 1950, 314
Gravity measurements in the Maritime Provinces, Canada, 314
Gravity observations, harmonic analysis, 163
Gravity reconnaissance of Island of Oahu, Hawaii, 358
Gravity, tidal variations of, 151
Green's function (non-steady) for infinite strip of a leaky aquifer, 330
Ground condition and cloudiness, influence on surface vapor pressure, 547
Ground ice and permafrost, techniques and equipment for study, 330
Ground water, committee report, 769
Ground water of Texas, nitrate in, 450
Guatemala, Santiaguito, volcanic activity, a geochemical study, 325
Gulf of Mexico, diurnal heating of surface, 565
Gulf of Mexico, temperature and moisture soundings over, 15
Gulf Stream, surface velocities, 324

Harmonic analysis of gravity observations, 163
Hawaii, gravity reconnaissance of Island of Oahu, 358
Heat and mass transfer networks of interest in water conservation, 49, 931
Heat flow and chemical segregation of mantle, 328
Heat flow, terrestrial, in Ontario and Quebec, 729
Heat, internal, of the Earth, control of cycles of glaciation by changes, 331
Heat-transfer and surface-temperature oscillations near ground, 189
Heat transfer, radiative, pressure dependence of, 319
Heated island, airflow over, 319
Heating, differential, of slopes, causes cross-valley winds, 319
Heating, diurnal, of the surface of the Gulf of Mexico, 565
Helium retentivity versus alpha activity in zircon and sphene, 313
Hydraulics of flow, rainfall, and infiltration in runoff computation, 780
Hydrodynamics (review), 127
Hydrograph (unit), related to basin characteristics, 332
Hydrographs (unit) and watershed characteristics, 591
Hydrologic-frequency analysis, general formula, 231
Hydrologic studies, soil-moisture measuring unit for, 447
Hydrology
  Abstracts and reviews, 127, 329
  Bibliography, 135, 295, 480, 622, 798, 949
  Discussions, 282, 283, 466, 467, 603, 607, 779, 780, 931, 932
  Minutes of Section, 493
  Papers, 49, 57, 66, 73, 222, 227, 231, 238, 245, 422, 443, 447, 450, 582, 591, 597, 739, 885, 891, 898, 903, 909
  Progress reports, 769, 772, 919
  Technical notes, 923, 927
Hydrology comes of age, 470

Ice (floating), air-coupled flexural waves in, 166
Ice sheet, floating, elastic waves in, 673
Icebergs in Baffin Bay and Davis Strait, and estimate of berg count off Newfoundland, 324
Icing conditions on Mount Washington and those encountered in flight, 179
Igneous petrology, theoretical, (review), 284
Index of names, 956
Index of subjects, 958
Index to Transactions, 1920-1944, 954
Infiltration, committee report, 919
Infiltration phenomena, pedological relations, 282
Infiltration, rainfall, and hydraulics in runoff computation, 780
Infrared emission, changes in, 679
Instrumentation for microclimatological factors, 833
Interception of rain and snow by ponderosa pine, 903
International cooperation on geodetic project, 106
International Union of Geodesy and Geophysics, Ninth General Assembly, 149, 299, 651, 785
Inversion, arctic, daily fluctuation of, 318
Ionospheric local disturbances, 320
Ionospheric winds, systematic, 321
Irrigation projects, phreatophyte control, 332
Isotopic (lead) ratios in age determinations, 313

Japan, formation of Syowa Sinzan, new volcano, 326
Jesuit Seismological Association, report, 110

Kinematic relationship in motion of storms, 849
Kinematic vortex theory and the anomalies of general circulation, 319

Laminar flow through granular media, porosity factor, 443
Lamont Geological Observatory, report on age studies, 313
Laplace azimuth control, accuracy in astronomic determinations, 314, 809
Lead isotopic ratios in age determinations, 313
Letters to the Editor, 120, 121, 123, 470, 783
Leveling, precision, at the White House, 315
Limestone terranes, hydrology and physiography, 772
Liminary zones, peri-continental, thermodynamic theory, 521
Long Island, fresh-water exchange of Great South Bay, 324

Magma production and extrusion, volume change, 327
Magnetic and electric fields about a rocket, 320
Magnetic anomalies at high altitudes, 397
Magnetic moment, six additional years of spontaneous increase, 322, 563
Magnetic Observatory at University of Houston, Texas, 322
Magnetic operations, airborne, 321
Magnetic work of U. S. Coast and Geodetic Survey, 279
Magnetic polarization of faulting in lower Witwatersrand shales, South Africa, 321
Magnetization of the Earth, increase of, 323
Magnetizations, contrasting, of flat-lying and folded paleozoic sediments, 336
Magnetograph, photo-electric, 322
Mantle, adiabatic gradient in, 41
Mantle, convection currents in, 531
Mantle, heat flow and chemical segregation, 328
Maryland, metamorphism in Howard and Montgomery counties, 335
Mass and heat transfer networks in water conservation, 49, 931
Mass movements in submarine canyon heads, 405
Massachusetts, Blue Hill, influence of ground condition and cloudiness on vapor pressure, 547
Meanders, river, origin, 898
Mediterranean Sea, heights of observed and computed local wind waves, 325, 878
Meeting
  Chicago, September 1952, 495, 954
  Fresno, California, February 1951, 495
  International Union of Geodesy and Geophysics, 149, 299, 651, 785
  Pasadena, California, February 1952, 807, 954
  Thirty-Second annual, 1951, 149, 487
  Thirty-Third annual, 1952, 495, 651, 807, 954
Meetings, committee report, 632
Membership, additions to, 300, 802
Metamorphism in Howard and Montgomery counties, Maryland, 335
Meteorology
  Abstracts, 318
  Bibliography, 129, 287, 475, 615, 790, 943
  Discussions, 775, 846
  Minutes of Section, 490
  Papers, 7, 15, 179, 189, 391, 547, 552, 683, 697, 701, 833, 849, 853
  Progress reports, 755, 760, 765
Mexico, Parícutin Volcano, 212, 327, 572
Mexico, geodetic work, 314, 601
Mexico, mirage behavior at Puerto Peñasco, 318
Microclimatological factors, instrumentation, 833
Microseismic study of cold-front passage over inland bodies of water, 315
Microseisms, origin and propagation, 315
Minutes
  Executive Committee meeting, 141, 628, 934
  General Assembly, 487
  Section of Geodesy, 489
  Section of Hydrology, 493
  Section of Meteorology, 490
  Section of Oceanography, 491
  Section of Seismology, 490
  Section of Tectonophysics, 494
  Section of Terrestrial Magnetism and Electricity, 491
  Section of Volcanology, 492
Mirage behavior at Puerto Peñasco, Mexico, 318
Mixing-length theory of tidal flushing, 419
Moisture accumulation rates in thunderstorm cells, 318
Moisture and temperature soundings over Gulf of Mexico, 15
Mount Washington, comparison of icing conditions with those encountered in flight, 179
Mountain building and convection-current hypotheses, 527
Mountain building, comment on, 528

New Jersey, wave forecasting at Long Branch, 325
New Mexico, phreatophyte control, 332
New York, fresh-water exchange of Great South Bay, 324
New York, summer rainfall, 701
Newfoundland, estimate of berg count from icebergs in Baffin Bay and Davis Strait, 324
Nicaragua, great eruption of Volcano Coseguina in 1835, 326
Nitrate in ground water of Texas, 450
Noise, low-frequency radio, 321
Normal circular distribution, 330
Notes, 138, 298, 483, 624, 799, 952

Oceanography at Texas A. and M. College, 324
Oceanography
  Abstracts, 323
  Bibliography, 132, 292, 478, 619, 796, 947
  Discussions, 777
  Geological, status in United States, 323
  Institute of, University of British Columbia, 112
  Minutes of Section, 491
  Papers, 31, 37, 201, 207, 405, 419, 595, 704, 719, 866, 875, 878
  Progress report, 112
Orogenic belts, properties, 514
Orthographic projections in structural geology, 912

Ozone, surface, at College, Alaska, 319, 552

Parícutin Volcano, 212, 327, 572
Particle paths in a plane, 222
Particle paths on unit sphere, 329
Pavement, erosion, formation and significance, 466
Pedological relations of infiltration phenomena, 282
Pegmatites, Fennoscandian, structural features, 328
Peri-continental liminary zones, thermodynamic theory, 521
Permafrost and ground ice, techniques and equipment for study, 330
Permeability, field methods for measuring, and soil anisotropy, 582
Personalia, 139, 298, 484, 625, 800, 952
Petrology and structural geology of Stone Mountain - Lithonia district, Georgia, 334
Phreatophyte control on irrigation projects, 332
Phreatophyte growth and water conservation, 333
Phreatophytes, eradication, South Pacific, 333
Phreatophytes, evapotranspiration, from climatological data, 332
Phreatophytes, relation to water, 333
Phreatophytes, use of water, in 2000-foot channel, 332
Physical and biological investigations in the Bering Sea and portions of the Arctic Ocean, 323
PKKP, P′P′, and the Earth's core, 373
Planetary scale of terrestrial phenomena, 536
Plastic flow and deformation within the Earth, colloquium, 147, 499
Plasticity of rocks in the Earth, 505
Porosity factor for laminar flow through granular media, 443
Postglacial uplift and gravity anomalies, 524
Pressure, atmospheric, and density to 160 km, 320
Pressure dependence of radiative heat transfer, 319
Probabilities from limited weather data, 318
Protons and aurora, 120

Radar altimetry operations of the U. S. Geological Survey, 314, 544
Radar echo, bright-band observations, 321
Radioactivity and carbon content of marine rocks, 881
Radioactivity of Round Lake and Elzevir Batholiths, 44
Rain and snow, interception by ponderosa pine, 903
Rain, onset from cumulus, 318
Rainfall frequency and climatic variation, 347
Rainfall in summer, New York, 701
Rainfall, infiltration, and hydraulics of flow in runoff computation, 780
Rainfall on small watersheds, 330
Rainfall over small areas, variations, 245, 932
Rayleigh disc (water) wave-direction indicator, theory, 325
Rayleigh waves from small explosions, 822
Recession curve, evaluation of two elements, 597
Recurrence interval of geomagnetic activity, 322, 861
Refraction, atmospheric, at College, Alaska, 114
Re-intrusion of serpentine, 462
Reviews and abstracts, 127, 284, 313-336
River meanders, origin, 898
Rock failure, research at Colorado School of Mines, 268
Rockburst seismology in South Africa, 317
Rocket, electric and magnetic fields, 320
Rocks, deformation of, 504
Rocks in the Earth, plasticity of, 505
Runoff computation, from rainfall, infiltration, and hydraulics, 730
Runoff, surface detention, land use, and erosion on small watersheds, 57

Safe yield in insular Ghyben-Herzberg system, 739
Sand classifier, improved, 923
Sand size and beach-face slope, 866
Sea floor, observations of velocity profile near, 207
Sea, gravity measurements, 314
Sedimentary rocks, elastic wave velocities, 173
Sediments, magnetizations of flat-lying and folded paleozoic, 336
Seepage into drain tubes in stratified soil, 422
Seepage rates with partial cutoff, 283
Seismological Association, Jesuit, report, 110
Seismological Laboratory, CIT, report, 749
Seismology
  Abstracts, 315
  Bibliography, 128, 287, 474, 615, 942
  Minutes of Section, 490
  Papers, 1, 166, 173, 373, 673, 822
  Progress report, 110, 749
  Rockburst, in South Africa, 317
Serpentine, re-intrusion of, 462
Shales in lower Witwatersrand, South Africa, abnormal polarization of faulting, 321
Shear fractures of Alaska and adjacent regions, 81
Sky, twilight, measurements of brightness, 320
Slope of beach, relation to sand size, 866
Snow and rain, interception by ponderosa pine, 903
Soil anisotropy and field methods for measuring permeability, 582
Soil-moisture measuring unit for hydrologic studies, 447
Soils, layered, numerical solutions for tile drainage, 779
Solar cycle and variation of geomagnetic activity, 322, 861
South Africa, abnormal polarization of faulting in lower Witwatersrand shales, 321
South Africa, rockburst seismology, 317
Special announcements, 149, 299, 495, 651, 807, 954
Specific-volume anomaly and current, graphical determination, 719

Spectrum, auroral, new band systems of nitrogen, 320
Sphere, unit, particle paths on, 329
Sporadic E activity, continental, 26
Storm rainfall over small areas, 245, 932
Storms, motion of, kinematic relationship, 849
Stratified flow, evaluation of critical regime, 329, 891
Stratigraphic viewpoints in measurement of geologic time, 313
Stress and strain in the outer solid shell of the Earth, 335
Stressed solid, chemical potential of, 251
Strontium method of age determination applied to lepidolite and biotite, 314
Structural contouring, subsurface, theory, 77
Structural geology, Stone Mountain - Lithonia district, Georgia, 334
Structural geology, use of orthographic projections, 912
Structural geology, Vesuvius Quadrangle, Virginia, 333
Structure of bed of Atlantic Ocean, 457
Structure of the mantle, and convection currents, 533
Submarine canyon heads, mass movements in, 405
Subsurface structural contouring, theory, 77
Surface-temperature and heat-transfer oscillations near the ground, 189
Swash and swash mark, 31
Symposium on measurement of geologic time, 306, 313
Symposium on phreatophytes, 311, 332

Tectonics of northeastern Venezuela, Carupano area, 259
Tectonophysics
  Abstracts, 333
  Bibliography, 137, 297, 482, 624, 799, 950
  Minutes of Section, 494
  Papers, 77, 81, 87, 251, 259, 268, 457, 462, 743, 912
Temperature and moisture soundings over Gulf of Mexico, 15
Temperature at boundary of Earth's core, 328
Temperature, effect of general circulation on, 319
Tensor analysis, application to geodesy, 157
Terminal velocity, behavior of water drops, 775
Terrestrial magnetism and electricity
  Abstracts, 320
  Bibliography, 131, 290, 477, 617, 792, 945
  Minutes of Section, 491
  Papers, 26, 397, 555, 563, 679, 861
  Progress report, 279
Terrestrial phenomena, study on planetary scale, 536
Texas, Magnetic Observatory at University of Houston, 322
Texas, nitrate in ground water, 450
Textures, rock, and crystallization, 328
Thermodynamic theory of peri-continental liminary zones, 521
Thunderstorm cells, moisture accumulation rates, 318
Tidal fluctuations and gravity flows in interconnected estuarine channels, 329, 653
Tidal flushing, mixing-length theory, 419
Tidal variations of gravity, 151
Tide-producing forces and artesian pressures, 369
Triangulation networks, a semi-rigorous method of adjusting, 372
Tripartite (Fordham's) station at Poughkeepsie, New York, 316
Tropics, high-level cyclones originating in, 683
Tuffs, welded, origin, 327
Turbulence, analyzing by photographs of airborne particles, 853
Turbulence flume to measure bed load, 123, 909

Ultra-rapid flow, Vedernikov's criterion, 603
Unit hydrographs and watershed characteristics, 332, 591
Upper atmosphere, committee report, 755

Vapor pressure, influence of ground condition and cloudiness, 547
Velocities, surface, in the Gulf Stream, 324
Velocity of radio waves, new determinations, 813
Velocity profile near the sea floor, 207
Venezuela, Carupano area, tectonics of, 259
Virginia, structural geology of the Vesuvius Quadrangle, 333
Volcanic activity at Santiaguito, Guatemala, a geochemical study, 325
Volcano Coseguina, Nicaragua, eruption in 1835, 326
Volcano Parícutin, 212, 327, 572
Volcano Syowa Sinzan, Japan, formation of, 326
Volcanology
  Abstracts, 325
  Bibliography, 134, 293, 480, 620, 797, 947
  Minutes of Section, 492
  Papers, 41, 44, 212, 572, 729, 881

Water and phreatophytes in western United States, 333
Water conservation through elimination of phreatophytes, 333
Water conservation, use of heat and mass transfer networks, 49, 931
Water, deep, total reflection of surface waves, 37
Water drops at terminal velocity in air, 697, 775
Water supply, role of aquifers, 227
Water temperature, wave steepness, and beach width, Carmel, California, 324
Water, use by phreatophytes in 2000-foot channel, 332
Water, wind-induced vertical movement on an open coast, 323
Watershed characteristics and unit-hydrograph parameters, 591
Watersheds, Coweeta, stream-flow frequency changes, 73

Watersheds, experimental, method for comparing flow, 331, 927
Watersheds (small), study of thunderstorm rainfall, 330
Watersheds (small), surface detention, runoff, land use, and erosion, 57
Wave-direction indicator (water), Rayleigh disc, theory for, 325
Wave forecasting methods applied to Long Branch, New Jersey, 325
Wave measurements at the Columbia River light vessel, 875
Wave patterns from explosions at 100 km, 316
Wave patterns indicate crustal structure, 316
Wave (shear), vibrational directions and fault movements, 317
Wave staff, electrical, 324
Wave steepness, water temperature, and beach width at Carmel, California, 324
Wave steepness (water), effect on wave velocity, 201
Wave train, propagation in infinitely deep water, 325
Wave velocities in sedimentary rocks, 173
Wave velocity (water), effect of wave steepness, 201
Waves, air-coupled flexural, in floating ice, 166, 316
Waves, forces exerted by, 777
Waves in non-artesian aquifers, 238
Waves observed and computed, 325, 878
Waves, radio, new determination of velocity, 813
Waves, Rayleigh, from small explosions, 317, 822
Waves, surface, reflection by deep water, 37
Weather data, limited, probabilities from, 318
Welded tuffs, origin, 327
White House, precision leveling, 315
Wind-induced vertical movement of the water on an open coast, 323
Wind waves, deep-water, observed and computed, 878
Winds, cross-valley, from differential heating, 319
Winds, systematic ionospheric, 321

X-ray intensities, soft, in the upper atmosphere, 320

TRANSACTIONS
AMERICAN GEOPHYSICAL UNION

Volume 32 FEBRUARY 1951 Number 1

ON PHENOMENA FORERUNNING EARTHQUAKES

Kenzō Sassa and Eiichi Nishimura

Abstract--Minute but clear and characteristic tilting motions of the ground were observed several hours before the occurrence of some destructive earthquakes at observatories near the epicenters. In this first report, the three most outstanding cases are discussed.

On September 1, 1923, Tokyo and its neighborhood were devastated by the great Kwanto earthquake. There were 246,540 casualties and 702,495 ruined buildings; this was historically the greatest earthquake damage in the world. In the following 27 years (1923-1950), 35 great and destructive earthquakes have occurred in Japan, causing enormously heavy losses of persons and materials. Hence it is natural, under these circumstances, that research for earthquake-proof construction and for methods to foretell earthquake occurrence occupy an important position in seismology in Japan. For the latter, various methods have been examined in recent years to detect phenomena forerunning earthquake occurrence, but it was very difficult to secure a clear and decisive one. It is likely that these forerunning phenomena, if they exist, may be very minute and may be observed only by suitable measuring instruments under very favorable conditions.

It was frequently observed that some great earthquakes brought about faults of large scale and land upheaval and sinking of considerable extent. And in some cases it was reported by witnesses that land upheaval of a number of meters was revealed by regression of sea water near the epicenter several hours before the occurrence of destructive earthquakes of coastal origin. These phenomena tell us that there exists an intimate relation between earthquake occurrence and crustal deformation. On the other hand, various phenomena were recently reported by some Japanese geophysicists, which suggest to us that the state or distribution of matter composing the Earth's crust in a particular region may change with time, and in some cases this change is related to seismic activity of that region. NISHIMURA [1950] deduced time variation of elasticity of the Earth's crust from tiltmeter observations at a station near the sea in Kyushu Province, and the range of change amounted to nearly 30 per cent of the mean value of elasticity. A paper on this result was first read in 1942 some time before it was published. SASSA [1948] and later HAYAKAWA [1950] of the Geological Survey, reported that they deduced from analysis of time-distance curves of some great earthquakes a change of about ten per cent in propagation velocity of seismic waves in the Earth's crust near the hypocenters before and after the occurrence of those earthquakes. In 1949, Okuda of the Geographical Survey, pointed out (not published) from his geodetic and astronomical survey that the direction of the plumb line at some points near the epicenter changed considerably before and after the great Nankai earthquake in December, 1946, and the angle reached several seconds. In 1949, changes of gravity value at these points were also observed with Vening Meinesz pendulums by Kumagai of Kyoto University (not published). Their amounts were about ten milligals. Hayakawa, in 1950 (not published), noticed that slight changes of gravity values related to seismicity were observed by the static gravimeter during exploration in the epicentral region of the severe Imaichi earthquake in December, 1949.

In general, many observations with geophysical instruments of high precision suffer directly or indirectly undesirable effects by variation of meteorological elements. Rainfall, for example, causes deformation of the surface ground of considerable amount and disturbs observation of minute tilting motion of the ground. Atmospheric temperature variation has a direct effect on the instrument itself and indirectly affects observation through the air and ground. Unequal expansion and contraction of parts of the instrument, change of elastic or magnetic properties of the instrumental material, and other similar changes are direct effects on the instrument by temperature change. The ground and buildings deformed by direct sunshine and temperature change. Change of barometric pressure and its sharp gradient also affect some geophysical measurements. For the purpose of avoiding these undesirable meteorological effects and observing minute change of geophysical phenomena accurately, it is recommended that the observation room be deep underground. Taking, as an example, an observation room deeper than 100 m below the ground surface, there is a diurnal variation in room temperature of less than 0.001° C and its annual change is less than 1° C, and meteorological, diurnal, and seasonal tilt of ground is not observed, and there is

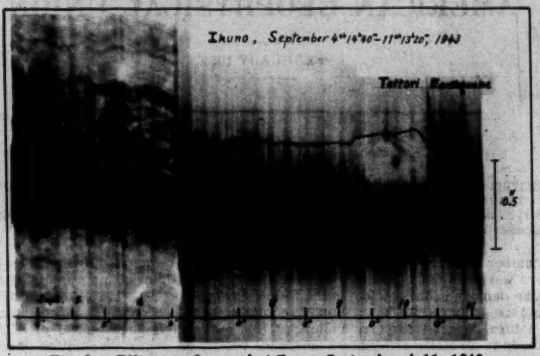


Fig. 1a--Tiltgram observed at Ikuno, September 4-11, 1943

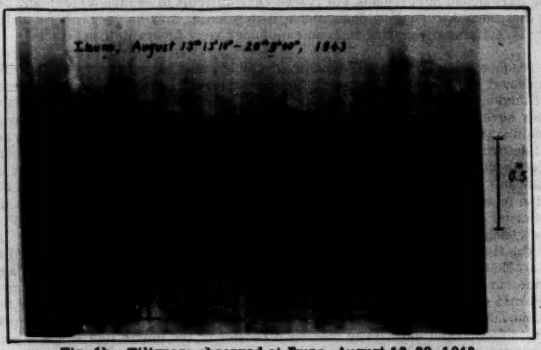


Fig. 1b--Tiltgram observed at Ikuno, August 13-20, 1943

little disturbance even by heavy rainfall.

Since 1937 we have been engaged in various geophysical measurements in deep observation rooms, profiting by the above described benefits. The observation stations were at four points in the beginning, but now number 15, including three new stations scheduled to be opened in 1950. Their depths below the ground surface are from some tens of meters to several hundred meters. The instruments used are designed mainly to observe the phenomena of crustal deformation cited, and variation in properties of crustal matter. There are 15 sets of tiltmeters of horizontal pendulum type, 15 sets of extensometers of the Sassa type, 15 sets of geomagnetic declinometers, ten sets of tiltmeters of mercury tube type, three sets of station gravimeters of double bifilar type, and other instruments of special purpose and design. All of these instruments were set in each deep underground observation room and their changes were recorded photographically on sensitive photographic paper wound around cylinders rotating one revolution per week. On the data and its analysis, many reports from various standpoints of phenomena have been published, and it is anticipated that many more will be in coming years. In this report, the phenomena forerunning earthquakes were observed and recorded with the above described instruments at the deeply seated underground rooms, will be discussed.

Since the beginning of observation in 1937, 22 destructive earthquakes have occurred in Japan,

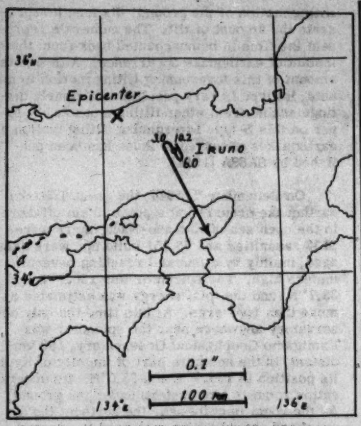


Fig. 2--Tilting motion of ground observed at Ikuno before the occurrence of the Tottori earthquake on September 10, 1943

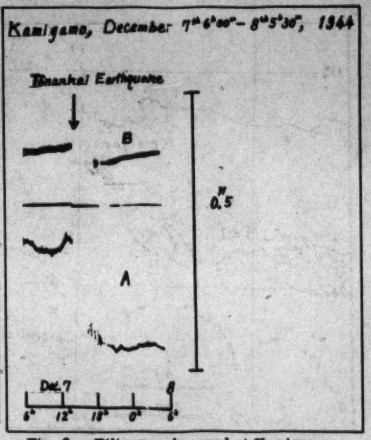


Fig. 3a--Tiltgram observed at Kamigamo, December 7-8, 1944

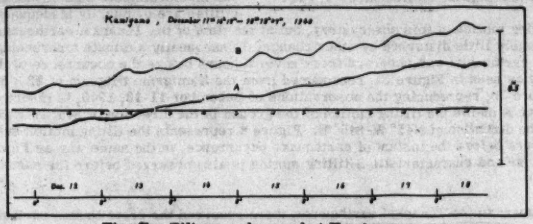


Fig. 3b--Tiltgram observed at Kamigamo, December 11-18, 1940

but only two of them had their epicenters within 100 km of our observation stations. But there were many cases in which rather strong, local earthquakes occurred close to the station. In this first report, the former two cases are the main ones reported; the latter will be reported in a succeeding report.

On September 10, 1943, a destructive earthquake occurred in the vicinity of the city of Tottori; there were 7348 casualties and 13,897 buildings were damaged. The position of the epicenter was 134.2° E and 35.5° N. The total energy of this earthquake was roughly estimated to be 10^{23} ergs. Our nearest observation station was Ikuno, 60 km distant from the epicenter at 134.8° E and 35.2° W; the observation room is in the adit of Ikuno Copper Mine, 800 m under the ground surface. The photographic sheet, 19 × 52 cm, recorded with tiltmeters at Ikuno during September 4-11, 1943, is reproduced in reduced size in Figure 1a. The record of usual days, August 13-20, 1943, is shown in Figure 1b for comparison. In these figures, the curves denoted as A and B show tilting motion of the ground in the direction of N43° W-S43° E and N47° E-S47° W, respectively. Curve E shows extension and contraction of ground in the direction of S88° E-N88° W, but this curve was not fully recorded at the time of earthquake as a result of partial breakdown of its illuminating lamp. In Figure 1a a peculiar tilting motion of the ground compared with the usual motion in Figure 1b, is observed, especially in Curve A, several hours before the Tottori earthquake. This is schematically expressed in Figure 2. In this figure, the arrowed line shows the direction of the

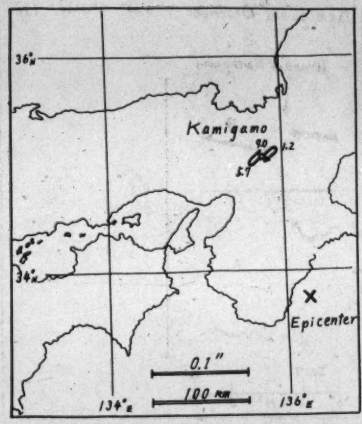


Fig. 4--Tilting motion of ground observed at Kamigamo before the occurrence of the Tōnankai earthquake on December 7, 1944

tilting motion of the ground. Its length represents the amount of tilt. The numerals represent the time in hours counted back from the instant of earthquake occurrence. Although the amount of this forerunning tilting motion is minute, its type is very peculiar and clearly distinguishable from other tilting motions. A paper on this S-type forerunning tilting motion of earthquakes observed at Ikuno has been published by SASSA [1944].

On December 7, 1944, the great Tōnankai earthquake occurred at a point 20 km offshore in the open sea of Kumano-Nada; there were 3133 casualties and 76,151 buildings were damaged, mainly by a tsunami reaching several meters high. The epicenter was 136.2° E and 33.7° N, and the total energy was estimated as more than 10^{24} ergs. At this time the only observatory anywhere near the epicenter was Kamigamo Geophysical Observatory, 160 km distant, in the northern part of the city of Kyoto. Its position is 135.7°E and 35.0°N. Its observation room is nine meters under the ground. As the room is quite near the surface, the diurnal and annual tilting motion of the ground (of thermal origin), in addition to Earth tidal change, are also recorded, together with various meteorological distrubances. Hence, facilities are ordinarily inadequate to observe minute tilting motion at this observatory, but at the time of the Tōnankai earthquake the record was fortunately little disturbed by other change. Consequently a minute forerunning tilting motion of the earthquake was observed there several hours before the occurrence of the Tōnankai earthquake as seen in Figure 3a, reproduced from the Kamigamo tiltgram of 22 × 55 cm original size. Figure 3b, reproducing the observations of December 11-18, 1940, is inserted for comparison. Curve A shows the tilting motion of the ground in the direction of S45° W-N45° E and Curve B that in the direction of N45° W-S45° E. Figure 4 represents the tilting motion schematically several hours before the instant of earthquake occurrence, in the same way as Figure 2. A minute but clear and characteristic S-tilting motion is also observed before the earthquake occurrence.

Subsequent to the Tōnankai earthquake, there occurred the great Nankai earthquake on

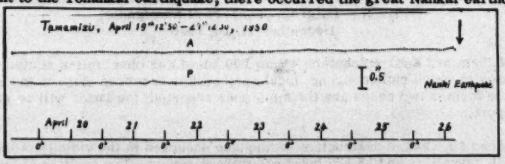


Fig. 5a--Tiltgram observed at Tamamizu, April 19-27, 1950

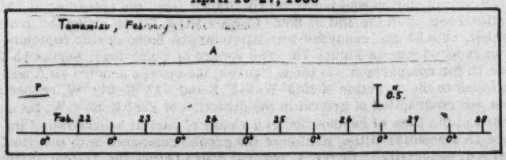


Fig. 5b--Tiltgram observed at Tamamizu, February 21-28, 1950

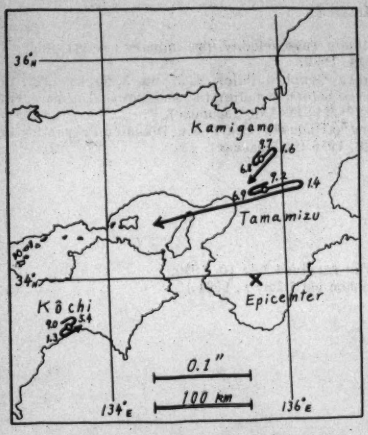


Fig. 6--Tilting motions of ground observed at Tamamizu, Kamigamo, and Kōchi before the occurrence of the Nanki earthquake on April 26, 1950

December 21, 1946, and the destructive Fukui earthquake on June 28, 1948. Of the epicenters, the former was 50 km off Kii Peninsula in the open sea, at 135.7° E and 33.0° N, and the latter close by the city of Fukui, at 136.3° E and 36.1° N. The total energies were estimated to be more than 10^{25} ergs and more than 10^{23} ergs respectively. A tsunami connected with the former caused great damage, and the latter destroyed Fukui and devastated its neighborhood. In each case the nearest observatory at the time was also Kamigamo Observatory, whose distances from the epicenters were 230 km and 115 km. In neither case were the peculiar forerunning motions detected on the tiltgrams recorded at Kamigamo. Two reasons are supposed for this; (1) the observatory was so remote from the epicenters that the forerunning tilting motion, if it existed, might be very minute; and (2) the tiltgrams in both cases were considerably disturbed by other tilting motions of the ground.

On April 26, 1950, the strong Nanki earthquake occurred on the southern part of Kii Peninsula. The epicenter was 135.8° E and 33.9° N, and the total energy was estimated at more than 10^{22} ergs, but the damage was small. At this time there were fortunately several observation stations near the epicenter, but the data for the nearest two points, 30 km and 50 km distant from the epicenter, were not satisfactory because of the breakdown of the recording equipment. The next nearest station was at Tamamizu in the southern part of Kyoto Prefecture at 135.8° E and 34.7° N, 80 km distant from the epicenter. The observation room is 30 m under the ground surface and the room condition is very favorable as seen in Figure 5a and b. Curve A shows tilting motion of the ground in the direction of N84° E-S84° W and Curve P shows test observation of the plumb-line variometer in the same direction. The tiltmeter was set only in one direction for the purpose of comparison with the P-instrument; Curve P disappears in both figures because of failure of the illuminating lamp. As seen in Figure 5a (original size 9 × 31 cm), a clear and characteristic tilting motion was recorded several hours before the earthquake occurrence. Although it was hard to trace a complete figure of the ground movement with a tiltmeter set only in one direction, the S-tilting motion observed at Tamamizu is schematically represented in Figure 6, together with the tilting motions observed at two other stations at Kamigamo and the city of Kochi, several hours before the occurrence of the Nanki earthquake. As Kamigamo is 120 km distant from the epicenter, and Kōchi (its observation room being 40 m under the ground surface) is 200 km distant from the epicenter, the forerunning tilting motions observed there were very minute and somewhat uncertain.

Comparing Figures 2, 4, and 6 with each other, it is concluded that a great or destructive earthquake is in gereral preceded by a minute and characteristic tilting motion of the ground of S-type several hours before its occurrence; observed tilts are of the order of magntide of 0."1 in angle at a distance of 100 km from the epicenter. It should be remarked here that the sense or direction of the S-turn motion referred to the position of epicenter was opposite in the two cases of the Tottori and Nanki earthquakes. This is an important fact to be studied, and within the present knowledge of these two cases it is interpreted to mean that this direction was related to that of the first motion of the ground caused by the seismic P-wave. That is, in the case of the Tottori earthquake, the first motion observed at Ikuno was a sinking, or in other words Ikuno was in the so-called pull-zone of the P-phase, and in the case of the Nanki earthquake, Tamamizu, Kamigamo, and Kōchi were all in the push-zone and their first motions were all upheaval of the ground. Kamigamo at the time of the Tōnanakai earthquake was on the border line of the push- and pull-zones. A detailed discussion of this item and of forerunning phenomena observed for several other earthquakes will be presented in a forthcoming second report.

References

HAYAKAWA, MASAMI, The variation of the seismic wave velocity (preliminary report), Rep. Geol. Surv., Japan, special number, pp. 7-24, 1950.

NISHIMURA, EIICHI, On Earth tides, Trans. Amer. Geophys. Union, v. 31, no. 3, pp. 357-376, 1950.

SASSA, KENZŌ, Tilting motion of ground observed before and after the destructive Tottori earthquake, Kagaku (Science), v. 14, no. 6, pp. 220-221, 1944 (in Japanese).

SASSA, KENZŌ, On some problems of foretelling earthquake occurrence, Disaster Prevention Research Inst., Kyoto Univ., Bull. 1, pp. 13-20, 1948 (in Japanese).

Geophysical Institute,
Faculty of Science,
Kyoto University,
Kyoto, Japan

(Communicated manuscript received July 10, 1950;
open for formal discussion until July 1, 1951.)

Transactions, American Geophysical Union Volume 32, Number 1 February 1951

FORCED CONVECTION CELL CIRCULATION IN CLEAR AIR

Patricia A. Langwell

(Contribution No. 527 of the Woods Hole Oceanographic Institution)

Abstract--The characteristics of a two-dimensional convection cell with an applied heat force are derived from the equations of motion, continuity, and the first law of thermodynamics. The solutions are compared with observations made over the water north of Puerto Rico. It is found theoretically that large, slow-moving cells can always exist, and will persist for one to two hours.

Introduction--Observations have shown that the lower atmosphere in the West Indies trade-wind region, near Puerto Rico, may be divided into several layers: the homogeneous layer, the cloud layer, and the air above the trade inversion [BUNKER and Others, 1949]. Within the cloud layer, clear areas with a diameter greater than 20 mi exist between patches of cumulus clouds. This paper is concerned with the characteristics of these clear areas.

Within the clear areas, horizontal traverses show oscillations of temperature and moisture which are 180° out of phase. Owing to the long over-water trajectory and the relatively isothermal sea surface, advective and diurnal changes may be disregarded. Moreover, this air is essentially non-turbulent. It was stated that the origin of these fluctuations is probably the residue of dissipated clouds [LANGWELL, 1948]. In this paper an attempt is made to approximate, in easily manipulated forms, the solution of the equations which describe the motion of air in a convection cell, when a heat source is added. The study was initiated in order to discover whether cool moist pockets under an inversion, in a conditionally stable atmosphere, could initiate cellular circulation. Because the temperature fluctuations are not assumed to be reinforced, denser air, moving downward to a lower inversion is replaced by warmer and drier air, which causes the cold source to become weaker. This effect is treated in the equations as a dissipative force.

Convective circulation may be initiated by heating at the base of the layer, or by cooling at the top. Because the amount of heat necessary to initiate the circulation at the base of the layer is no less than the degree of coolness necessary at the top, a heat source rather than a cold source may be included in the equations. For mathematical convenience, the former has been used. The scale of the model (no larger than ten to 20 km) justifies the assumption of a flat, non-rotating Earth, but the inclusion of the heat source suggests the less usual assumption of a compressible atmosphere in which a heat source can produce density changes. Ideally, the temperature would appear as an arbitrary function of height. Because this paper attempts to give only approximate solutions, this degree of refinement is not used, and the temperature is assumed to be constant, or to vary as a linear function of elevation. In the latter case, only a first approximation to the solution is given. Since this paper is concerned with slow-moving cells in clear air, the equations include none of the effects of condensation.

Historical background--STOMMEL [1947] has usefully discussed the literature dealing with convective phenomena. His paper is one of an extensive collection of reports on this subject, which also contains a paper by MUNK [1947] stating that the Coriolis force may be ignored in the analysis of convection cells of the size studied below.

It would be impractical to list all the works within this large field. The papers described below represent those which most nearly approximate the type of problem and approach to be discussed here.

The first of these studies is that of LOVE [1891] who studied the effect on an incompressible fluid of a stream function which is assumed to be periodic in horizontal distance and time. If the percentual decrease of density with height is constant, the variation of the streamline with height is the product of an exponential and a periodic function. The next treatment of interest is that of BJERKNES and Others [1934, pp. 361 and 396]. Because they used Lagrange's equations, it is difficult to compare their results with those of the present paper. DOPORTO [1945], in his study

of the isopycnic layer, translated their equations into the Eulerian form. His values of the free oscillations can be shown, by a change in notation, to be the same as those calculated below for an isothermal atmosphere. More recently STARR [1949] has included a heat source in a treatment of the problem of convection, using a method is some respects similar to Love's. The present paper differs from its predecessors in the attempt to include the concept of a heat source while using the method of Bjerknes and Doporto.

Method--A coordinate system is chosen with the origin at the base of the layer, moving with the speed of the undisturbed wind, and the x-axis is oriented in that direction. If the wind shear is is neglected, the undisturbed velocities vanish throughout the layer. The basic equations of the problem are the equations of motion, and that of continuity. Within this moving coordinate system, the problem is treated in two dimensions, and the cells are assumed to be of infinite extent in the third dimension.

The equations of motion are written as

$$Du/Dt = -(1/M)\,\partial P/\partial x \quad \ldots\ldots (1)$$

and

$$Dw/Dt = -g - (1/M)\,\partial P/\partial z \quad \ldots\ldots (2)$$

where u and w are the horizontal and vertical perturbation velocities, M is the total density, P is the total pressure, and g is the gravitational force. The equation of continuity is

$$(1/M)\,DM/Dt + (\partial u/\partial x + \partial w/\partial z) = 0 \quad \ldots\ldots (3)$$

As the fourth equation, the first law of thermodynamics, as applied to a unit mass of an ideal gas, is used in the form

$$(1/M)\,DM/Dt = (1/\lambda P)\cdot DP/Dt - (R/c_p)(M/P)\,Q(x, z, t) \quad \ldots\ldots (4)$$

where R and c_p have their usual meanings, $\lambda = c_p/c_v$, and Q(x, z, t) is the rate at which heat is added to the system.

The atmosphere is assumed to be in hydrostatic equilibrium before the disturbance. If the undisturbed conditions are denoted by a zero subscript, this may be represented schematically as

$$\partial p_o/\partial z = -\rho_o g$$

and

$$\partial p_o/\partial x = 0$$

The usual assumptions involved in the use of the perturbation method [HAURWITZ, 1941] are made, only the first order terms being retained. This permits reduction to the following simplified forms

$$\partial u/\partial t = -(1/\rho_o)\partial p/\partial x \quad \ldots\ldots (5)$$

$$\partial w/\partial t = -(1/\rho_o)(\partial p/\partial z + g\rho) \quad \ldots\ldots (6)$$

$$\partial \rho/\partial t + w\,\partial \rho_o/\partial z + \rho_o(\partial u/\partial x + \partial w/\partial z) = 0 \quad \ldots\ldots (7)$$

$$\partial \rho/\partial t + w\,\partial \rho_o/\partial z = (1/\lambda RT_o)(\partial p/\partial t + w\partial p_o/\partial z) - (R\rho_o{}^2)Q(x, z, t)/c_p p_o \quad \ldots\ldots (8)$$

where ρ and p are perturbation density and pressure, respectively.

Since these four equations involve six unknowns, further information is necessary, in order to integrate the equations. If the temperature and heat source are known as functions of height, it is possible to find u, w, p, and ρ. The isothermal case and that of the constant lapse-rate will be considered below. The rate of heat added to the system, Q, is always assumed to be a first order perturbation term of the form

$$Q(x, z, t) = Q(x, t)\, e^{-\phi z}$$

The basic assumption concerning the form of the solutions is that

$$u, w, p, \rho, Q \propto A, B, C, D, E \exp(i\mu x - \gamma t) \quad \ldots\ldots\ldots\ldots\ldots (9)$$

where the amplitudes of the perturbation quantities are functions of height alone. The horizontal dimension of the cell is π/μ, and γ is the damping factor which describes the dissipation effect on the heat source due to the circulation itself. It may also be considered that γ includes a measure of the effect of friction.

Isothermal atmosphere--If the assumption is made that $dT_o/dz = 0$, then from the hydrostatic equation and the equation of state one obtains

$$\partial \rho_o / \partial z = -\rho_o g / RT_o$$

Substitution of this value and the set of assumptions (9) into the equations makes it possible to express the equations in terms of height alone. It may then be seen that

$$-\gamma A = -i\mu C/\rho_o \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (10)$$

$$-\gamma B = -(1/\rho_o)(dC/dz + gD) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (11)$$

$$-\gamma D - \rho_o g B/RT_o + \rho_o(i\mu A + dB/dz) = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (12)$$

$$-\gamma D - \rho_o g B/RT_o = -\gamma C/\lambda RT_o - \rho_o g B/\lambda RT_o - R\rho_o^2 E/c_p p_o \quad \ldots\ldots\ldots\ldots\ldots (13)$$

Since A may be eliminated by using (10), the subtraction of (13) from (12) gives the result that

$$\rho_o dB/dz - \rho_o g B/\lambda RT_o - (\mu^2/\gamma + \gamma/\lambda RT_o)C = R\rho_o^2 E/c_p p_o \quad \ldots\ldots\ldots\ldots\ldots (14)$$

The coefficient of density D may be eliminated between (11) and (12), so that

$$g dB/dz - (\gamma^2 + g^2/RT_o)B + (\gamma/\rho_o)\, dC/dz - \mu^2 g C/\rho_o \gamma = 0 \quad \ldots\ldots\ldots\ldots\ldots (15)$$

From (14), it can be seen that

$$dC/dz = [\rho_o \gamma/(\mu^2 \lambda RT_o + \gamma^2)]\, [-(R/c_v)\, dE/dz + \lambda RT_o\, d^2B/dz^2$$
$$- g db/dz - (g/RT_o)(-RE/c_v + \lambda RT_o dB/dz - gB)] \quad \ldots\ldots\ldots\ldots\ldots\ldots (16)$$

If the expressions for C and dC/dz are substituted into (15), the resultant equation is

$$d^2B/dz^2 - (g/RT_o)\, dB/dz - (\mu^2 + \gamma^2/\lambda RT_o + \mu^2 g\Gamma/\gamma^2 T_o)B$$
$$- (g/\lambda R^2 T_o^2 + \mu^2 g/\gamma^2 \lambda RT_o)RE/c_v \quad \ldots\ldots\ldots\ldots\ldots\ldots (17)$$

where Γ is the dry adiabatic lapse rate. It will be assumed that $E = E' e^{-\phi z}$, where ϕ is a positive constant and E' is the value of the heat source at $z = 0$. With this assumption, together with the fact that (17) has constant coefficients, the equation may be easily solved. The general solution is

$$B_h = B_1 e^{r_1 z} + B_2 e^{r_2 z}$$

where

$$r = g/2RT_o \pm \sqrt{g^2/4R^2 T_o^2 + \mu^2 + \gamma^2/\lambda RT_o + \mu^2 g\Gamma/\gamma^2 T_o}$$

where the plus sign is used for r_1 and the minus for r_2. The total solution is

$$B = B_1 e^{r_1 z} + B_2 e^{r_2 z} + B_3 e^{-\phi z} \quad \ldots\ldots\ldots\ldots\ldots\ldots (18)$$

where

$$B_3 = [-\phi/c_pT_o - (g/\lambda R^2T_o^2 + \mu^2 g/\gamma^2\lambda RT_o)R/c_v]E'/$$
$$[\phi^2 + g\phi/RT_o - (\mu^2 + \gamma^2/\lambda RT_o + \mu^2 g\Gamma/\gamma^2T_o)]$$

If B_3 were to become infinite, the solutions would not satisfy the conditions of the perturbation method. Since $\phi > 0$, the denominator of B_3 vanishes only if

$$\phi = -g/2RT_o + \sqrt{g^2/4R^2T_o^2 + \mu^2 + \gamma^2/\lambda RT_o + \mu^2 g\Gamma/\gamma^2T_o}$$

The quantities in this equation are presented in a following section on evaluation of the roots. They give an approximate value for ϕ of 0.8×10^{-5}/cm. Since the value of ϕ used in the problem is 10^{-5}/cm, B_3 needs no modification to allow for a singularity. Later changes in the problem, due to the introduction of a lapse-rate, will not change the value of B_3 sufficiently to introduce this difficulty.

Since the solution above is exact, the approximations below must approach it as the lapse rate approaches zero. The solutions below, however, represent a more realistic atmosphere.

Constant lapse-rate--If it is assumed that $dT_o/dz = -\delta$, where δ is a constant, it is found that

$$\partial\rho_o/\partial z = -\rho_o(g - R\delta)/RT_o$$

This value must be substituted in (7) and (8). The set of assumptions (9) is applied, with the result that the form of (14) and (15) is unchanged. Since the temperature is now a function of height

$$dC/dz = \rho_o\gamma\left\{-(R/c_v)\,dE/dz + \lambda RT_o\,d^2B/dz^2 - (g + \lambda R\delta)dB/dz\right.$$
$$\left. + (-RE/c_v + \lambda RT_o\,dB/dz - gB)[-(g - R\delta)/RT_o + \mu^2\lambda R\delta/(\mu^2\lambda RT_o + \gamma^2)]\right\}/$$
$$(\mu^2\lambda RT_o + \gamma^2) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (19)$$

When (14), (15), and (19) are combined

$$d^2B/dz^2 - [g/RT_o - \mu^2\lambda R\delta/(\mu^2\lambda RT_o + \gamma^2)]\,dB/dz - [\mu^2 + \gamma^2/\lambda RT_o$$
$$+ \mu^2 g(\Gamma - \delta)/\gamma^2T_o + \mu^2 g\delta/(\mu^2\lambda RT_o^2 + \gamma^2T_o)]B = (1/c_pT_o)\,dE/dz$$
$$- [(g - R\delta)/RT_o - \mu^2\delta/(\mu^2\lambda RT_o^2 + \gamma^2T_o) + \mu^2 g/\gamma^2\lambda RT_o]RE/c_v \quad \ldots\ldots\ldots\ldots (20)$$

In order that the equation be integrable in simple functions, it is necessary to replace $T_o(z)$ by T, the average temperature through the height interval. The substitution of T for T_o results in an error no greater than two per cent. With this limitation, the general solution of the homogeneous equation is

$$B_h = B_1e^{r_1z} + B_2e^{r_2z}$$

where

$$r = g/2RT - \mu^2\lambda R\delta/2(\mu^2\lambda RT + \gamma^2)$$
$$\pm\sqrt{[g/2RT - \mu^2\lambda R\delta/2(\mu^2\lambda RT + \gamma^2)]^2 + \mu^2 + \gamma^2/\lambda RT + \mu^2 g(\Gamma - \delta)/\gamma^2T + \mu^2 g\delta/(\mu^2\lambda RT^2 + \gamma^2T)}$$

The particular solution is $B_3e^{-\phi z}$, and B_3 may easily be calculated from the differential equation by substituting this expression in the equation.

In order to simplify the equations, the numerical values of the physical model will be substituted into these results, before the boundary conditions are applied. It must be noted, therefore, that while the preceding equations are reasonably general, the work which follows applies only to the specific problem described below.

Evaluation of the roots--In a previous paper [LANGWELL, 1948], the author described observations made over the water north of Puerto Rico. (For further data on this region, see also BUNKER and Others [1949].) Within the "cloud" layer, which is a conditionally stable region about two kilometers thick bounded above and bl low by inversions, a horizontal period of about

12 mi is observed in the temperature and moisture measurements taken through the extensive clear areas. These periods are 180° out of phase. The amplitude of the variations increases with height. This results in cold moist sacs being found below the upper limit of the cloud layer. It was suggested that these sacs, probably the residue of dissipated clouds, would initiate cellular motion within the layer. The horizontal extent of a cell is assumed to be half the period of the temperature variations. The heat source is assumed to decrease with height at the same rate as the cold pockets decrease from the upper inversion downward. The range of temperature for a horizontal traverse was measured at two heights, and an exponential decrease assumed between them. The following values have been substituted in the evaluation of the roots.

$R = 2.87 \times 10^6$ cm^2/sec^2 deg
$\Gamma = 10^{-4}$ deg/cm
$T = 285°$ K
$\lambda = 1.4$
$\mu = 3 \times 10^{-6}$/cm, $\mu^2 = 9 \times 10^{-12}$/cm^2
$g = 980$ cm/sec^2
$\delta = 0.6 \times 10^{-4}$ deg/cm
$\phi = 10^{-5}$/cm

Further, the value $\gamma = 10^{-4}$/sec was chosen as appropriate to the data. If $\gamma = 10^{-3}$, the disturbance is reduced by e^{-1} in about 15 min, and would be difficult to observe. On the other hand, if $\gamma = 10^{-5}$, a reduction by e^{-1} would take over a day.

It is then found that, to a high degree of approximation,

$$g/2RT - \mu^2\lambda R\delta/2(\mu^2\lambda RT + \gamma^2) = 5 \times 10^{-7} = (g/2RT - \delta/2T)/\text{cm}$$

$$\sqrt{[g/2RT - \mu^2\lambda R\delta/2(\mu^2\lambda RT + \gamma^2)]^2 + \mu^2 + \gamma^2/\lambda RT + \mu^2 g(\Gamma - \delta)/\gamma^2 T + \mu^2 g\delta/(\mu^2\lambda RT + \gamma^2)}$$
$$= 3 \times 10^{-4} = \mu\sqrt{g(\Gamma - \delta)/T}/\gamma/\text{cm}$$

and

$$B_3 = E'/c_p(\Gamma - \delta) \text{ cm/sec}$$

It can be seen from the above that it is reasonable to state that

$$B = B_1 e^{\mu/\gamma\sqrt{g/T(\Gamma - \delta)}z} + B_2 e^{-\mu/\gamma\sqrt{g/T(\Gamma - \delta)}z} + E'e^{-\phi z}/c_p(\Gamma - \delta) \quad \ldots\ldots\ldots\ldots (21)$$

Boundary condition--In order that cellular motion exist, it is necessary that w and hence B, vanish at the base and at some other height, h. If these conditions are imposed on B, the relationship between B_1 and B_2 may be expressed as

$$B_1 + B_2 = -E'/c_p(\Gamma - \delta)$$

and

$$B_1 e^{\mu/\gamma\sqrt{g/T(\Gamma - \delta)}h} + B_2 e^{-\mu/\gamma\sqrt{g/T(\Gamma - \delta)}h} + E'e^{-\phi h}/c_p(\Gamma - \delta) = 0$$

To the degree of approximation that

$$e^{-\mu/\gamma\sqrt{g/T(\Gamma - \delta)}h} = e^{-60} = 0$$

$$B = E'[-e^{-\phi h} e^{-\mu/\gamma\sqrt{g/T(\Gamma - \delta)}(h - z)} - e^{-\mu/\gamma\sqrt{g/T(\Gamma - \delta)}z} + e^{-\phi z}]/c_p(\Gamma - \delta) \quad \ldots\ldots (22)$$

The vertical component of the velocity may now be written as

$$w = E'e^{i\mu x - \gamma t}[-e^{-\phi h} e^{-\mu/\gamma\sqrt{g/T(\Gamma - \delta)}(h - z)} - e^{-\mu/\gamma\sqrt{g/T(\Gamma - \delta)}z} + e^{-\phi z}]/c_p(\Gamma - \delta)$$

or, taking the real part,

$$w = E'e^{-\gamma t}\cos\mu x[-e^{-\phi h} e^{-\mu/\gamma\sqrt{g/T(\Gamma - \delta)}(h - z)} - e^{-\mu/\gamma\sqrt{g/T(\Gamma - \delta)}z} + e^{-\phi z}]/c_p(\Gamma - \delta) \quad (23)$$

After the value for B is inserted in (14), the real part of the perturbation pressure is

$$p = \rho_o E' e^{-\gamma t} \cos\mu x \, [e^{-\phi z} (\gamma(\Gamma - \delta)/\mu^2 T - \gamma g/\mu^2 \lambda RT - \gamma\phi/\mu^2)$$
$$+ e^{-\phi h} e^{-\mu/\gamma\sqrt{g/T(\Gamma - \delta)}(h - z)} (\gamma g/\mu^2 \lambda RT - \sqrt{g(\Gamma - \delta)/T}/\mu)$$
$$+ e^{-\mu/\gamma\sqrt{g/T(\Gamma - \delta)}z} (\gamma g/\mu^2 \lambda RT + \sqrt{g(\Gamma - \delta)/T}/\mu)]/c_p(\Gamma - \delta) \quad \ldots\ldots\ldots\ldots (24)$$

Similarly, it may be seen from (10) that

$$u = E' e^{-\gamma t} \sin \mu x \, [e^{-\phi z} (-(\Gamma - \delta)/\mu T - g/\mu\lambda RT - \phi/\mu)$$
$$+ e^{-\phi h} e^{-\mu/\gamma\sqrt{g/T(\Gamma - \delta)}(h - z)} (g/\mu\lambda RT - \sqrt{g(\Gamma - \delta)/T}/\gamma)$$
$$+ e^{-\mu/\gamma\sqrt{g/T(\Gamma - \delta)}z} (g/\mu\lambda RT + \sqrt{g(\Gamma - \delta)/T}/\gamma)]/c_p(\Gamma - \delta) \quad \ldots\ldots\ldots\ldots (25)$$

The last three equations are the perturbation quantities which describe the cellular motion. Each is a separable function of x, z, and t. In order to make these results as clear as possible, the velocities are discussed as a function of each variable. It can be seen from (23) and (25) that, at a given point in space

$$u = U_1 e^{-\gamma t}$$

and

$$w = W_1 e^{-\gamma t}$$

where U_1 and W_1 are constants determined by the x and z. The circulation, therefore, dies out exponentially with time. At a given height and time

$$u = U_2 \sin \mu x$$

and

$$w = W_2 \cos \mu x$$

where U_2 and W_2 are constant at any z and t, and x varies from 0 to π/μ. The horizontal velocity vanishes at the edges of the cell, and reaches a maximum at $x = \pi/2\mu$, while the vertical velocity is a maximum at one edge, decreasing monotonically to a minimum at the other. For a given time and location (in x)

$$u = U_3 \{e^{-\phi z} [-(\Gamma - \delta)/\mu T - g/\mu\lambda RT - \phi/\mu]$$
$$+ e^{-\phi h} e^{-\mu/\gamma\sqrt{g/T(\Gamma - \delta)}(h - z)} (g/\mu\lambda RT - \sqrt{g(\Gamma - \delta)/T}/\gamma)$$
$$+ e^{-\mu/\gamma\sqrt{g/T(\Gamma - \delta)}z} (g/\mu\lambda RT + \sqrt{g(\Gamma - \delta)/T}/\gamma)\}$$

and

$$w = W_3 [- e^{-\phi h} e^{-\mu/\gamma\sqrt{g/T(\Gamma - \delta)}(h - z)} - e^{-\mu/\gamma\sqrt{g/T(\Gamma - \delta)}z} + e^{-\phi z}]$$

Table 1--The change of the perturbation velocities with height

z	u/U_3	w/W_3
cm		
2×10^5	- 15.4	0
1.8×10^5	- 0.68	0.16
1.5×10^5	- 0.74	0.22
10^5	- 1.2	0.37
10^4	+ 0.52	0.88
10^3	+ 79.1	0.29
10^2	+110	0.04
10	+114	0.01
0	+114	0

where U_3 and W_3 are constant, and z varies from zero to two kilometers. In Table 1, the values are presented in the reverse of the usual order, as an aid to visualization.

The large values of u/U_3 through the uppermost and lowest meter of the cell are due to the dominance of the terms involving γ^{-1} through these height intervals. Complete symmetry of the terms from the free oscillations is prevented by the rapid damping of the heat source with height. The oscillation of u/U_3 is caused by the relative importance of the first term through the center of the layer. It will be noted that the

horizontal velocity changes sign well below the midpoint of the interval, at about the same height as w/W_3 reaches a maximum. The circulation is deformed by the decrease of the heat source with height, in such a way that the mass transport through the lowest 100 m is counterbalanced by motion through the remaining 1900 m.

Discussion of results--In the previous section, it was shown that the two equations determining B_1 and B_2 are inhomogeneous. Solution of these equations is possible for all non-trivial values of E' and h. Cellular motion can always exist through any height interval of an atmosphere disturbed from hydrostatic equilibrium by a heat source. Because the perturbation velocities and pressure are proportional to $E'/(\Gamma - \delta)$, the amplitude of the disturbance is directly proportional to the magnitude of the heat source and inversely proportional to the stability. For a given source, the magnitude of the disturbance decreases with increasing thickness of the layer. The characteristics of the solutions given above are in agreement with what might be qualitatively expected. Since the purpose of this paper is to determine whether the circulation started by the sinking of the denser air is sufficient to initiate cellular motion of any duration, it is necessary to know the value of E' (the rate at which heat must be added to the system to maintain motions of the required scale). If w is never greater than 5 cm/sec at any height

$$5 = E'/c_p(\Gamma - \delta)$$

and

$$E' = 4.8 \times 10^{-5} \text{ cal/gm sec}$$

In order to evaluate the effectiveness of the temperature difference available, the first law of thermodynamics is used. As a first approximation, it is assumed that dp = 0. It may then be stated that

$$- E'\Delta t = - c_p \Delta T$$

Since a temperature difference from the surrounding air as great as 1.2° K is generally observed at 6000 ft or higher

$$\Delta t \approx 6000 \text{ sec}$$

It is thus reasonable to estimate that the sacs of cold air initiate cellular motion which persists for one to two hours.

The factors omitted from this problem are the curvature of the Earth, its rotation, and the wind shear. Those included are the compressibility of the atmosphere, a localized heat source, a self-dissipative term, and a qualitative measure of a constant lapse-rate. Within this framework, it has been shown that the cellular motion set up by the cold sacs would be maintained for one to two hours.

Since the temperature fluctuations are largest in the non-turbulent air, and the temperature and moisture vary oppositely, making the virtual temperature less variable than the dry-bulb temperature, the assumption that these fluctuations are initially caused by dissipated clouds seems probable [LANGWELL, 1948]. It is therefore reasonable to expect that they would be regenerated several times a day. The combination of these two factors is sufficient to make such cells a semi-permanent feature of this weather situation.

Possible extensions--The equations used in this paper may be modified in several ways, to extend the solution to other problems. If the coordinate system is presumed to be fixed, a constant wind is added, and $-\gamma$ is replaced by $-\gamma + i\mu u_0$ in Eq. (10) to (13). A velocity of the circulation relative to the undisturbed wind may also be included by assuming that the perturbations are of the form $\exp[i\mu(x - ct) - \gamma t]$. The term $-\gamma + i\ (u_0 - c)$ will replace $-\gamma$ in the perturbation equations. The problem may still be solved by the same techniques, but both terms of the exponential are complex, and some manipulation is required to reduce the solutions to a usable form. Similarly, the inclusion of the third dimension and a constant Coriolis force will add to the length of the equations, but not to the mathematical difficulty of the problem. However, it is beyond the scope of this type of solution to deal any more exactly with wind shear or a variable Coriolis parameter than has been possible with the temperature lapse-rate.

Acknowledgments--The author desires to thank the members of the Woods Hole Oceanographic Institution for their assistance, and especially B. Haurwitz for his continued help and encouragement. The work was initiated under contract with the Bureau of Ships, and continued under the sponsorship of the Office of Naval Research.

This paper was presented in partial fulfillment of the requirements for the degree of doctor of philosophy in meteorology at New York University.

References

BJERKNES, V., J. BJERKNES, H. SOLBERG, and T. BERGERON, Hydrodynamique Physique, Presses Univ. France, 3 v., 1934.

BUNKER, A. F., B. HAURWITZ, J. S. MALKUS, and H. STOMMEL, Vertical distribution of temperature and humidity over the Caribbean Sea, Pap. Phys. Oceanogr. and Met., Mass. Inst. Tech. and Woods Hole Oceanogr. Inst., v. 11, no. 1, 1949.

DOPORTO, MARIANO, Cell motion in the atmosphere, Dept. Ind. Comm., Met. Sec., Dublin, Tech. Note no. 6, 1945 (unpublished).

HAURWITZ, B., Dynamic meteorology, McGraw-Hill, 1941.

LAMB, H., Hydrodynamics, Dover Pub., 1945.

LANGWELL, PATRICIA A., Inhomogeneities of turbulence, temperature and moisture in the West Indies trade-wind region, J. Met., v. 5, pp. 243-246, 1948.

LOVE, A. E. H., Wave motions in a heterogeneous heavy liquid, Proc. London Math. Soc., v. 22, p. 307, 1891.

MUNK, WALTER H., Effect of Earth's rotation upon convection cells, Ann. N. Y. Acad. Sci., v. 48, Art. 8, pp. 815-820, 1947.

STARR, V., A mathematical theory of convection, J. Met., v. 6, pp. 188-192, 1949.

STOMMEL, HENRY, A summary of the theory of convection cells, Ann. N. Y. Acad. Sci., v. 48, Art. 8, pp. 715-726, 1947.

Department of Meteorology,
College of Engineering,
New York University,
New York 53, New York

(Manuscript received April 14, 1950; presented before the American Meteorological Society at the time of the Thirty-First Annual Meeting, Washington, D. C., May 2, 1950; open for formal discussion until July 1, 1951.)

Transactions, American Geophysical Union Volume 32, Number 1 February 1951

TEMPERATURE AND MOISTURE SOUNDINGS OVER THE GULF OF MEXICO FOR MARCH, 1949

John R. Gerhardt

Abstract--A series of temperature and moisture soundings made every four hours on a nearly continuous basis during March, 1949 for heights up to about 45 ft above the surface of the Gulf of Mexico at an offshore drilling station near Freeport, Texas are used to demonstrate the modification of an air mass by a water surface. The observations confirm the logarithmic distribution of water vapor, the previously observed variation of the evaporation coefficient with wind speed, and the essential similarity of the heat and moisture transfer processes.

Introduction--As the result of a series of conferences between personnel of the Humble Oil Company and the Electrical Engineering Research Laboratory of the University of Texas on the meteorological aspects of microwave propagation, a program of overwater temperature and moisture soundings was initiated early in 1949. The Humble Oil Company's interest in this problem came as a direct result of their attempts to maintain radio and radar liaison between their offshore oil-drilling platforms in the Gulf of Mexico, their supply boats, and their shore installations. Since most of these communication and radar links involved the use of electromagnetic energy of microwave frequencies, it soon became apparent that a correlating study of various meteorological parameters over the Gulf would be very helpful in explaining the variations in the propagation of this microwave energy. In order to get the necessary measurements, arrangements were made to use the facilities of an existing drilling platform located offshore in the Gulf of Mexico east of Freeport, Texas.

It should be emphasized that while these measurements are among the very few that have been made over the open Gulf, they are nevertheless only of a preliminary nature; and the results presented here should be interpreted in this light. It is hoped that similar observations may be taken in the near future to cover longer periods of time and to obtain information on temperature, moisture, and wind gradients to higher levels.

The measurement program--The drilling platform was located approximately four miles offshore in the Gulf of Mexico and approximately five miles east of Freeport, Texas. The total installation consisted of a wooden platform about 40 by 60 ft whose surface, supported by a uniform array of about 40 piles, was 36 ft above mean sea level, with a 300-ft ship (LST) anchored permanently by the platform. The long axis of the ship-platform ensemble was oriented NW-SE, or approximately perpendicular to the shoreline in the Freeport area. Figure 1 is a map showing the relative orientations of the oil-drilling rig and the Texas coastline.

Sounding stations were located at the two seaward corners of the platform. The easternmost station operated normally under surface wind directions from N through SE, and the southernmost station under wind directions from SE through W. Due to possible air contamination from the ship and platform, data taken with surface winds within +45° of NW were held to a minimum and only two out of the 62 observations reported upon here were concerned with wind directions in this quadrant. A good deal of care had to be taken to insure representativeness of the data due to the activities and equipment peculiar to oil-drilling platforms. Measurements could not be taken during periods of severe platform vibration. Under surface winds of three mph or less, heat from engines and pumps located topside near the center of the platform could be detected at all levels greater than 50 ft above the platform, and ejected steam could mushroom out underneath a large portion of the platform. However, by using a sounding station which

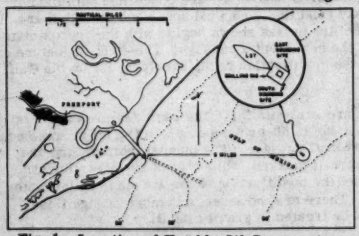


Fig. 1--Location of Humble Oil Company's drilling rig off Freeport, Texas

could be correlated with surface wind direction, and by restricting observations to those periods with wind speeds of four to five miles per hour or greater, the measurements of temperature and moisture reported upon here, limited to heights of about 50 ft above the surface, are considered representative of free air conditions. Certainly while some unrepresentative effects may have been present in a few of the observations, no systematic unrepresentativeness was possible.

The general problem of obtaining representative overwater soundings is difficult, and only a few sets of reliable measurements have been made. Most of the previous work has been done by using the masts and rigging of a ship, but great care has to be taken there to insure that the ship itself is not influencing the observations. However, significant observations have been made in this manner by WÜST [1937], MONTGOMERY [1940], and Black [SVERDRUP, 1946]. The airplane is probably the best current method for taking overwater soundings. The use of an airplane enables one to obtain soundings to much greater heights at a greater number of locations and reduces the relatively large fluctuations observed in temperature and moisture measurements over water by integrating the measurements over long distances. The best results using such a system have been reported by CRAIG [1946], EMMONS [1947], and BUNKER [1949]; but the loss of detail near the surface and the difficulty of fitting an airplane into a continuous schedule are factors which limit the effectiveness of such a sounding procedure. Although shore-based soundings are not generally representative of overwater conditions, they can be made under certain conditions. Using trade-wind circulation and a Caribbean island location, KATZIN [1947] has obtained significant sets of data from a shore-based tower.

In the present study the motor aerated wet- and dry-bulb psychrograph developed in the Radiation Laboratory, Massachusetts Institute of Technology [KATZ, 1947] was used to obtain the temperature and moisture data. Using a rope and pulley arrangement with a single psychrograph, soundings were made at four-hour intervals by recording dry- and wet-bulb readings at each of six to eight levels above the water surface. A minimum period of two minutes was allowed for the thermistors to reach equilibrium with air temperature and moisture at each level. Measurements are accurate to $\pm 0.1^\circ$ C but demonstrate a spread of about 0.3° C from a mean gradient due to inherent fluctuations. A mercury thermometer was used to obtain Gulf surface temperatures, and the values obtained here may be in error up to about 0.5° C. A three-cup anemometer and wind vane located four feet above platform level and extending five feet out from the easternmost edge of the platform was used to observe wind speed and direction. Auxiliary observations included present weather, sky condition, and state of the sea surface.

Presentation of data--Temperature and moisture soundings were made at the Freeport offshore location from February 28 to April 6, 1949 when cessation of drilling activities and dismantling of the platform terminated the measurement program. Although an attempt was made to maintain the scheduled four-hour intervals in the sounding program, spells of bad weather, operating difficulties, and damage from occasional high waves forced an approximate 50 per cent reduction in the total number of soundings over this mentioned period. As a result, only two periods are presented here for more detailed study: (1) from 04^h00^m March 3 to 00^h00^m March 7; and (2) from 20^h00^m March 14 to 04^h00^m March 21.

Since a primary feature of the observations lies in their time continuity, an effective method of presentation is given in Figures 2 to 7 where temperature and moisture values of the Gulf surface and the overlying air at the five- and 45-ft levels are shown as a function of time. Figures 2, 4, and 6 present the time variation of these temperatures in degrees centigrade for the periods March 3-7, 14-18, and 18-21, respectively, while Figures 3, 5, and 7 are concerned with the corresponding moisture variations. General weather, sky condition, and wind speed and direction are also shown for the time of each observation. Each of the series shown begins with the approximate aftermath of a frontal passage, and carries on to the next frontal passage. The striking feature of these observations lies in the type and degree of the modification of the overlying air by the Gulf surface.

From a qualitative viewpoint, the six figures are very similar. The basic features are a fairly rapid addition of heat or moisture to the air over a 36- to 60-hr period, a leveling off at some equilibrium value, and a rapid fall following the next frontal passage. The diurnal temperature and moisture variation of the Gulf surface is small but well marked, while that of the overlying air usually appears only under those conditions in which the modification of the air mass by the water surface has reached an approximate equilibrium. There are, however, a number of significant differences among the patterns and these will now be treated in greater detail.

It would perhaps be best at first to note that a general weather pattern consistent with the observed winds and temperature and moisture time traces can be found in the southeasterly movement

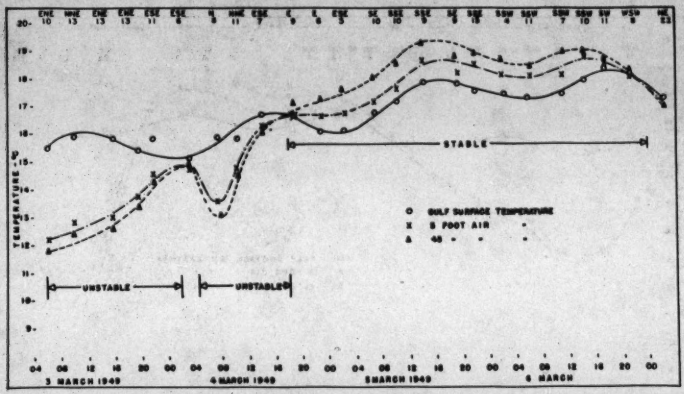


Fig. 2--Temperature of Gulf surface and overlying air at five and 45 ft for the period March 3-7; wind speed (mph) and direction 40 ft above the water

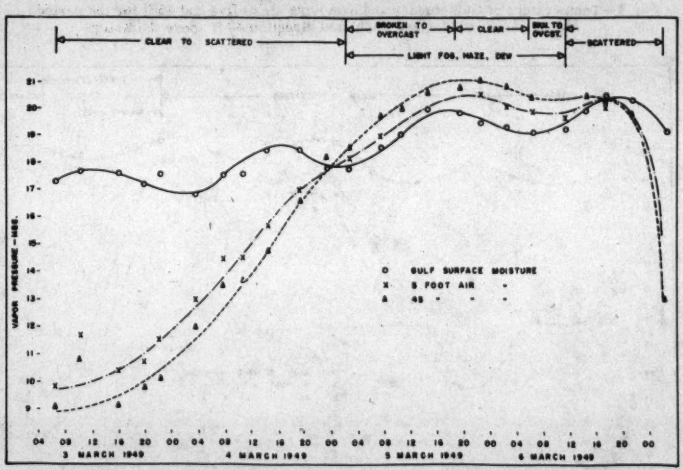


Fig. 3--Moisture values of Gulf surface and overlying air at five and 45 ft for the period March 3-7; average weather and sky conditions are shown at the top of the figure

of a high pressure cell over the Gulf of Mexico following the frontal passage. The veering of surface winds from N through S is then equivalent to an ever-increasing distance of overwater travel until the air over the site has effectively originated from a mid or southern Gulf of Mexico source region. Thus, the gradual increase of air temperature and moisture which takes place as surface winds veer from north to south can be construed as representing a change in the source properties of the air mass. Note that while the final nearly-constant air-temperature values are always in excess of the measured water-surface temperature, the moisture values may or may not exceed equivalent water-surface moisture.

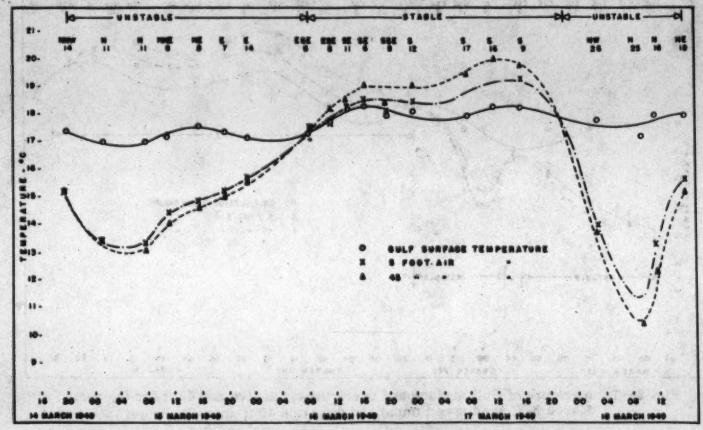


Fig. 4--Temperature of Gulf surface and overlying air at five and 45 ft for the period March 14-18; wind speed (mph) and direction 40 ft above the water

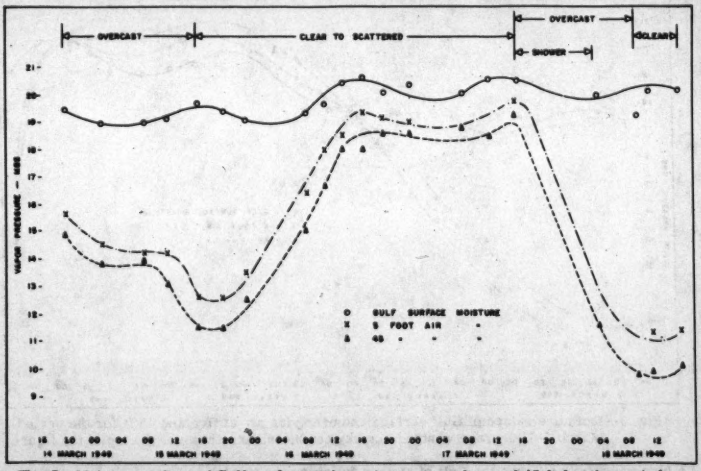


Fig. 5--Moisture values of Gulf surface and overlying air at five and 45 ft for the period March 14-18; average weather and sky conditions are shown at the top of the figure

Figures 2 and 3 are remarkably similar and with the exception of a small unexplained temperature variation from 04^h00^m to 08^h00^m on March 4, both the air temperature and moisture values show a uniform increase from the start of the period to approximately 16^h00^m March 5, at which time approximately constant levels are reached. Note that both temperature and moisture

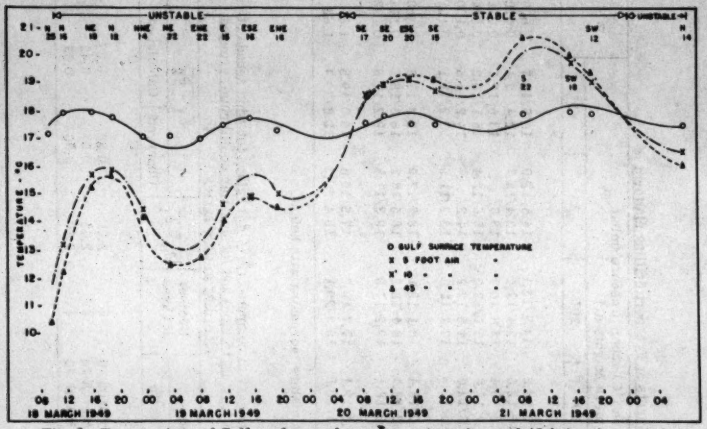


Fig. 6--Temperature of Gulf surface and overlying air at five and 45 ft for the period March 18-21; wind speed (mph) and direction 40 ft above the water

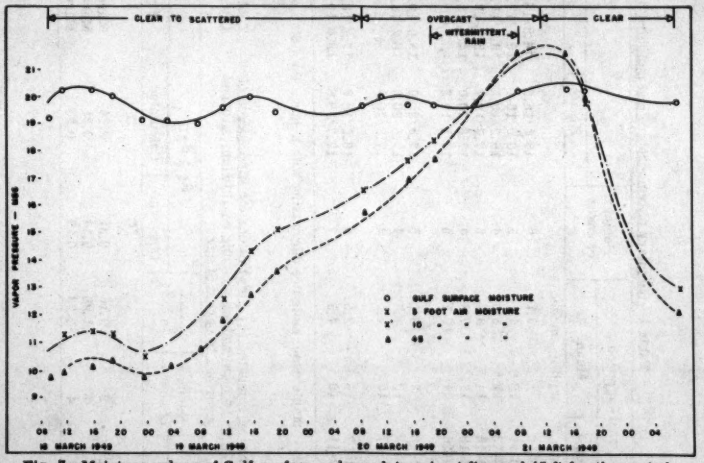


Fig. 7--Moisture values of Gulf surface and overlying air at five and 45 ft for the period March 18-21; average weather and sky conditions are shown at the top of the figure

exceed the Gulf surface values, and that the moisture is high enough to cause essential saturation of the overlying air for a period of over 30 hr. The front passed the drilling station between $22^h 00^m$ March 6 and $02^h 00^m$ March 7.

Table 1--Summary of temperature and moisture measurements at Freeport drilling platform

Case	Class	Wind speed Range	Wind speed Mean		Number of cases	Temperature (°C) vapor pressure (mbs) at mean heights (ft) Sfc	5′	10′	20′	30′	45′	$\overline{\Gamma}$
		mph	mph	m/sec								
A	I	6- 8	7	3.1	6	16.6/18.5	14.8/13.8	14.7/13.3	14.7/13.1	14.6/12.9	14.6/12.7	0.069
A	II	10-11	10.5	4.7	5	16.0/18.1	13.6/12.9	13.5/12.6	13.4/12.4	13.4/12.2	13.4/12.1	0.078
A	III	12-13	12.5	5.6	4	16.2/18.1	13.8/11.0	13.8/10.4	13.6/10.2	13.6/ . .	13.5/10.1	0.041
A	IV	14-15	14.5	6.5	5	17.3/19.4	15.3/13.0	15.2/12.8	15.1/12.5	15.0/12.4	15.1/12.2	0.064
A	V	16-18	17	7.6	4	17.8/20.0	14.7/13.0	14.6/12.6	14.5/12.2	14.2/ . .	14.2/11.6	0.100
A	VI	22-26	24	10.7	5	17.3/19.3	. . / . .	13.5/12.3	13.2/11.8	13.2/11.5	13.2/11.1	0.151
B_1	VII	6- 8	7	3.1	5	17.8/20.0	18.0/18.6	18.0/18.4	18.1/18.1	18.2/17.9	18.3/17.6	0.340
B_1	VIII	9-12	10.5	4.7	4	17.8/20.0	18.2/18.6	18.3/18.4	18.4/18.3	18.5/18.2	18.6/18.1	0.144
B_1	IX	15-17	16	7.1	4	17.8/20.0	. . / . .	19.0/18.1	19.2/17.9	19.3/17.8	19.2/17.6	0.192
B_2	X	4- 7	5.5	2.5	4	16.6/18.6	17.3/18.9	17.4/19.1	17.7/19.3	17.9/19.6	18.0/19.8	1.81
B_2	XI	9-11	10	4.5	7	17.7/19.6	18.0/19.8	18.1/20.0	18.3/20.1	18.4/20.3	18.6/20.4	1.63

A = Unstable case. B_1 = Stable case, moisture decreasing with height. B_2 = Stable case, moisture increasing with height.

Table 2--Summary of computed $(\theta_1 - \theta_2)$ values for wind speeds of Class I, II, III, IV (≤16 mph) and for unstable equilibrium, grouped according to period of day

Time From	Time To	Number of cases	$\overline{\theta_s - \theta_1}$	$\overline{\theta_1 - \theta_2}$ Observed	$\overline{\theta_1 - \theta_2}$ Calculated
			°C	°C	°C
06^h00^m	11^h59^m	8	2.16	0.31	0.34
12 00	19 59	7	1.98	0.14	0.31
20 00	05 59	4	2.23	0.12	0.35

Table 3--Summary of computed $(\theta_1 - \theta_2)$ values for wind speeds of Class I, II, III, IV (≤16 mph) and for unstable equilibrium, grouped according to time series

Period From	Period To	Number of cases	$\overline{\theta_s - \theta_1}$	$\overline{\theta_1 - \theta_2}$ Observed	$\overline{\theta_1 - \theta_2}$ Calculated
			°C	°C	°C
March 3	March 6	8	2.01	0.30	0.32
March 14	March 18	7	2.65	0.07	0.42
March 18	March 22	4	2.10	0.30	0.33

The period of March 14-18, shown in Figures 4 and 5, is superficially similar to that of the previous example. Constant temperature and moisture values are reached at the same time, although air moisture is now significantly less than surface moisture. A basic anomaly, however, occurs in the first 36 hr of the period where it is noted that while air temperature begins increasing at approximately 06^h00^m March 15, air moisture decreases for an additional ten to 12 hr beyond 06^h00^m. SVERDRUP [1946] states " . . . . there exists no large difference in the process by which heat and water vapor are diffused . . . . " so the explanation of the discrepancy requires an examination of the assumptions usually made in the theory of diffusion by eddy transport. Using the notation of LETTAU [1949],

$$Q = -cA\,\partial q/\partial z$$

expresses the intensity of the turbulent flux, Q, of a property, q, in a layer of air within the atmospheric surface layer. A is an Austausch coefficient and c is a factor which depends on the units of Q and q. Thus, for the transfer of heat

$$L = -cpA\,\partial\theta/\partial z$$

where θ is the potential temperature. The basic assumptions here are those of a uniform horizontal q-distribution and an identical Austausch coefficient for all air properties. Now in the period represented by Figures 4 and 5, there is an obvious advection of both heat and moisture following the frontal passage. From a re-examination of the surface synoptic data, it is found that the advection of air with decreasing moisture content continues for some 12 hr after a uniform horizontal temperature distribution had been attained. In this case, then, the decrease in air moisture due to advective effects was more than sufficient to offset the normal evaporation from the sea surface. The passage of a front occurred between 17^h00^m March 18 and 03^h00^m March 19.

The third series of March 18-22 shown in Figures 6 and 7 demonstrates still another type of anomaly in the concept of equivalence of heat and moisture transfer. Smoothing the large scale diurnal variations of temperature, it should be noted that the transition period from uniform addition of heat and moisture to constant values does not occur at the same time, and that moisture values, in fact, keep increasing almost up to the time of the passage of the front. Obviously, there must have existed a source of moisture other than the sea surface, and the observations of rain from the period 20^h00^m March 20 to 08^h00^m March 21 confirm this hypothesis. Note that the time of beginning of rain came within a few hours of the transition in the slope of the temperature traces. The frontal passage occurred between 18^h30^m and 22^h00^m, March 21.

The evaporation coefficient and the equivalence of heat and moisture transport--Although it is not possible to specify completely or analyze the temperature and moisture distributions over water from vertical sounding data at a single location due to the possible presence of horizontal gradients, certain conclusions and comparisons can be drawn concerning the expected lapse rates. In order to smooth out most of the individual irregularities in the original data, they have been summarized in Table 1 according to increasing values of the wind speed at 40 ft. Average temperature and humidity values are presented, but only the moisture measurements will be considered in more detail and compared with previous investigations by Montgomery, Sverdrup, Wüst, and others. It will, however, be demonstrated that the diffusion processes for temperature and moisture for these sets of data are similar. Stable and unstable cases have been treated separately, with the former subdivided into cases with moisture both increasing and decreasing with height. No attempt has been made to classify the data according to degree of stability.

Although a comparison will be made between the observations presented here and previous open sea results, it is realized that the proximity of a land mass will introduce complications and the measured lapse rates of temperature and moisture may not always have reached a condition of approximate equilibrium with the underlying surface. In fact it will be shown later that there are certain basic differences. However, inasmuch as the comparisons will be limited to those cases involving unstable equilibrium and the resultant unhindered diffusion of heat and water vapor, it is believed that the relatively short distances of overwater travel involved for certain wind directions will not be too serious although the exact degree of difference between the two cases is yet to be determined. Certainly, any modification of an air mass by a water surface is a function of the temperature and moisture differential between air and sea surface and is thus ultimately a function of the original source properties of the air. But it is only in the case of stable equilibrium (warm air moving over cooler water) that the distance of overwater travel is important in specifying the vertical temperature and moisture gradients. Overwater travel for unstable equilibrium is essentially equivalent to a more or less uniform addition of heat and moisture at all levels through the

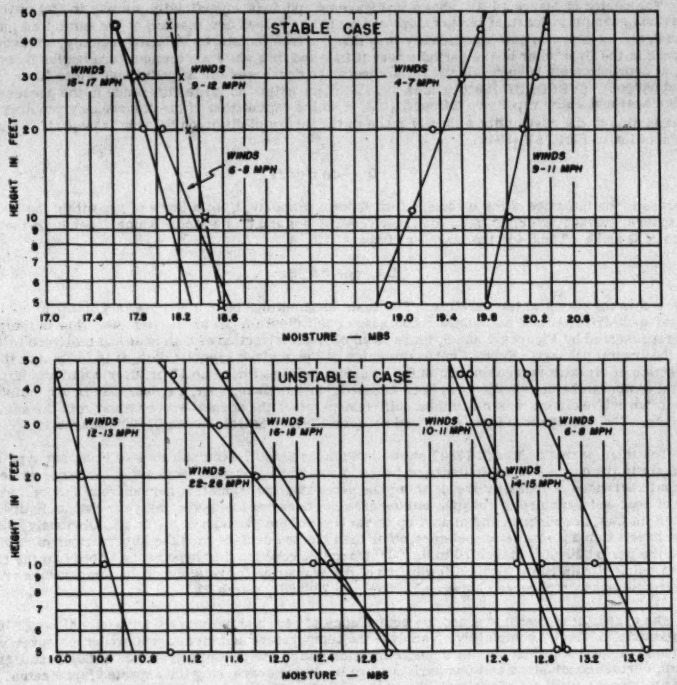


Fig. 8--Average vertical distributions of water vapor shown as a function of mean wind speed for stable and unstable conditions (from Table 1)

mixing zone, which is proportional to the mean wind speed, and is of the order of 2000 ft. Incidentally, note that the classification of the data in Table 1 into stable and unstable cases is also equivalent to a classification by wind direction and overwater travel since unstable temperature gradients occurred almost exclusively with winds from N through ENE while stable gradients were restricted to winds from E through SW.

It is worthy of note that all of the mean humidity gradients of Table 1 follow the now well-recognized logarithmic height law as shown in Figure 8. It is unfortunate that measurements to higher levels were not feasible, especially in the case of moisture increasing with height, for it would be interesting to compare the total height of such a layer with the theoretical height of the logarithmic layer for neutral stability which Montgomery has predicted to be about 40 m for a mean wind speed of six meter/second.

In order to describe the vertical gradient of water vapor, MONTGOMERY [1940] introduced a dimensionless quantity, Γ, the evaporation coefficient

$$\Gamma = -[1/(e_s - e_a)]\,\partial e/\partial \log_e z \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where e_s is the vapor pressure at the sea surface, e_a is the vapor pressure at a standard level above the sea surface, and z the height above the surface. If the vapor pressure is a linear function

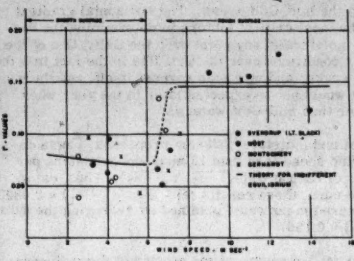


Fig. 9--Theoretical and average measured values of Γ as a function of wind speed for unstable equilibrium

of the logarithm of height, it can be shown that

$$\Gamma \equiv [(e_a - e_b)/(e_s - e_a)]/\log_e (b/a) \quad . . (2)$$

where e_b is the vapor pressure at the height b.

Since the initial theory has been developed by Montgomery and extended by Sverdrup, it suffices here to state that theoretical values of Γ have been determined for the unstable case as shown in Figure 9. This curve, which has been taken from SVERDRUP [1946], is derived from the fact that the sea surface changes from a smooth to a rough surface rather abruptly at a wind speed of about six to seven meters per second, and the change in Γ is a result of the increase in the resistance coefficient. The calculated values of $\overline{\Gamma}$ (mean values of Γ for each class in part A of Table 1) for the Freeport unstable data agree fairly well with the previously published results of Montgomery, Sverdrup, and Wüst, although the change from a smooth to a rough surface takes place at a slightly higher mean wind speed.

The $\overline{\Gamma}$ values for the stable case cannot as yet be compared to a corresponding theoretical distribution, although some recent theoretical work has been done in this field. CRAIG [1949], in a very fine paper on the vertical eddy transfer of heat and water vapor in stable air, determined some calculated mean values of a constant, $G_H = \chi\gamma_H\Gamma_H$. The corresponding calculated values of Γ (assuming $\Gamma_H = \Gamma$, and $\chi\gamma_H = 2 \times 10^{-2}$) are all within the rather low range of 0.034 to 0.046 and show no significant variation with wind speed or degree of stability, while SVERDRUP [1946] predicts that values should be higher for the stable case. Although these two views are not in agreement, neither lends credence to the large values of $\overline{\Gamma}$ reported here for the stable case. The discrepancy apparently lies in the fact that, while theoretically the limit of $(e_a - e_b)/(e_s - e_a)$ should be constant as $(e_s - e_a)$ approaches zero, such was not always the case for the data considered here. True, Montgomery does not evaluate Γ when $(e_s - e_a) < 1$ mb (a = 4 meters), "because the error is large when the air is nearly saturated with respect to the water," but it still appears that Γ must be used with some care for describing the humidity gradient.

Fundamentally, of course, all such disparities lie in the fact that the requirements of a uniform horizontal temperature and moisture field both for water surface and for overlying air were not exactly fulfilled. Even the open ocean does not have a zero gradient of sea surface temperature, but, for the most part, the gradients are small enough that few errors are introduced. The fact, however, that the Γ values did fall so close to the theoretical values for the unstable case in spite of the inherently large gradients of sea surface temperatures that can be present in the Gulf coastal waters is an indication that the surface uniformity criterion is not too inflexible. In fact, it is possible to make a qualitative estimate of what the magnitude of the Gulf surface-temperature gradient must have been to have given rise to the observed inversions of vapor pressure. The value is of necessity minimal in nature for the assumptions are that the theoretical neutral stability values of Γ hold for the stable case, and that the moisture value at the 45-ft level is not only a maximum value but that no appreciable decrease in moisture occurred at this level as a result of travel over cooler surface water. Thus, from (2), we proceed as follows

Γ (average theoretical neutral stability value for a smooth surface) = 0.082

e_{45} (average of classes X and XI, Table 1, moisture increasing with height under stable conditions) = 20.1 mb

$e_5 - e_{45}$ (average of classes I through V, moisture decreasing with height under unstable conditions, winds 7.6 m/sec or less) = 1.0 mb

$\therefore e_5$ (average value existing with e_{45} at mid-Gulf source regions under above assumptions) 20.1 + 1.0 = 21.1 mb

$\therefore e_s$ (Eq. (2)) = $1.0/[0.082 \times \log_e (45/5)] + 21.1 = 26.7$ mb

This value of e_s is equivalent to a water surface temperature of about 22.3° C and it represents an increase of from two to four degrees centigrade over the measured Gulf surface temperature values at the oil drilling platform. As a comparison, a chart of average sea-surface temperatures for a 20-yr period for the month of March [U. S. WEATHER BUREAU, 1938] shows a gradient of

about 10° F from the Gulf shore near Galveston to the mid-Gulf areas. The horizontal gradient of sea surface temperature will, in fact, be one of the most critical factors in determining the resultant vertical gradients of air temperature and moisture at any point over the Gulf. One of the basic features of a change from summer to winter conditions over the Gulf lies in the fact that the sea surface temperature gradient becomes much weaker and may even reverse itself, and the winter and early spring fog conditions near the coast would not be expected later in the year when Gulf waters near the coast are as warm or warmer than mid-Gulf waters.

In order the check the similarity between heat and moisture diffusion processes, $\overline{\Gamma}$ was determined for the unstable case for all values of wind speed less than 16 mph (seven meters per second) by comparing theoretical and mean values of the ratio, $(\overline{e_1 - e_2})/(\overline{e_s - e_1})$. Thus, using the average theoretical value of Γ for the unstable case, there results $(\overline{e_1 - e_2})/(\overline{e_s - e_1}) = 0.0825 \log_e (45/5) = 0.181$. This compares with the measured mean value obtained by averaging the data for classes I to IV in Table 1 of $(\overline{e_1 - e_2})/(\overline{e_s - e_1}) = 0.159$.

Now, following SVERDRUP [1946], in order to get a measure of the scatter of the indivudual values of this ratio, values of $(\overline{e_1 - e_2})$ were plotted against the corresponding values of $(\overline{e_s - e_1})$ for the 20 unstable cases in which the wind speed was less than 16 mph. Although there were an insufficient number of points to warrant definite conclusions, there were indications of the effect of the nearby land masses on the resulting moisture distributions. Thus while the correlation coefficient between the two sets of data of +0.26 is of the same order of magnitude as that reported by Sverdrup, the slope of the regression line of $(\overline{e_1 - e_2})$ on $(\overline{e_s - e_1})$ is only +0.036, a value approximately one-fifth that of the theoretical. It seems possible that an explanation might lie in the fact that large scale advective phenomena could give rise to periodic independent variations in the value of $(\overline{e_s - e_1})$ in addition to the normal inherent random variations in $(\overline{e_1 - e_2})$.

If heat is transported by the same process as moisture, we should have $(\overline{\theta_1 - \theta_2}) = 0.159 (\overline{\theta_s - \theta_1})$, where θ is the potential temperature at the heights considered. In order to check this value, temperature data is grouped into two classifications, using all data for the unstable cases in which the wind speed is less than 16 mph. For the first case, the data are grouped according to the time of the day when the data were taken, and in the second case, according to the individual time series. Results are presented in Tables 2 and 3.

The above values show that, although the predicted values exceed the calculated values in every instance, the expected decrease in potential temperature was satisfactorily predicted during the morning sunlight hours and during the first and third time series. Note that the thermally unstable portion of these two series was that in which the diffusion processes of heat and moisture appeared most alike from a study of the temperature and moisture time sequences.

Acknowledgments--Although pesonnel of the Electrical Engineering Research Laboratory were instrumental in setting up the sounding station, acknowledgment is hereby made to Sidney Martin and to Andrew Pierson of the Exploration Department of the Humble Oil Company for their untiring efforts as sole observers and technicians at the sounding site for the greater part of the measurement program. The research and measurement program herein reported upon was made possible through support extended the Electrical Engineering Research Laboratory of the University of Texas by the U. S. Navy (Office of Naval Research) under contracts N5ori-136, Project Order I and N6onr-266, Task Order II.

References

BUNKER, ANDREW F., Marine meteorology, Reference no. 49-23, Woods Hole Oceanographic Institution, 38 pp., 1949.

CRAIG, RICHARD A., Measurements of temperature and humidity in the lowest 1000 ft of the atmosphere over Massachusetts Bay, Papers in Phys. Oceanog. and Met., v. 10, no. 1, 47 pp., 1946.

CRAIG, RICHARD A., Vertical eddy transfer of heat and water vapor in stable air, J. Met., v. 6, pp. 123-133, 1949.

EMMONS, GARDNER, Vertical distributions of temperature and humidity over the ocean between Nantucket and New Jersey, Papers in Phys. Oceanog. and Met., v. 10, no. 3, 89 pp., 1947.

KATZ, I., An airplane psychrograph, Bull. Amer. Met. Soc., v. 28, pp. 363-370, 1947.

KATZIN, M., R. BAUCHMAN, and W. BINNIAN, Three- and nine-centimeter propagation in low ocean ducts, Proc. Inst. Radio Eng., v. 35, pp. 891-905, 1947.

LETTAU, H., Isotropic and non-isotropic turbulence in the atmospheric surface layer, Geophys. Res. Paper No. 1, Air Force Cambridge Research Laboratories, 86 pp., 1949.

MONTGOMERY, R. B., Observations of vertical humidity distribution above the ocean surface and their relation to evaporation, Papers in Phys. Oceanog. and Met., v. 7, no. 4, 30 pp., 1940.
SVERDRUP, H. U., The humidity gradient over the sea surface, J. Met., v. 3, pp. 1-8, 1946.
UNITED STATES WEATHER BUREAU, Charts of average sea-surface temperature (°F) by months for the years 1912-1931, Washington, D. C., 1938.
WÜST, GEORG, Temperatur- und Dampfdruckgefalle in den untersten Meters über der Meeresoberflache, Met. Zs., v. 54, pp. 4-9, 1937.

Electrical Engineering Research Laboratory,
The University of Texas,
Austin 12, Texas

(Communicated manuscript received March 3, 1950, and, as revised, October 31, 1950; open for formal discussion until July 1, 1951.)

CONTINENTAL SPORADIC E ACTIVITY

N. C. Gerson

Sporadic E ionizations indicated a very interesting motion or drift during the period June 17-18, 1949, over North America. The reflections were reported from 23^h00^m GMT on the 17th to 05^h00^m GMT on the 18th, by radio amateurs operating mainly in the frequency range 50-54 mc/s. The amateurs, whose cooperative spirit and interest in this venture contributes directly towards its success, report a sporadic E observation whenever radio contact is made with another amateur by means of the E_s layer. The reports are then carefully screened to insure that the mode of propagation may not be attributed to ground wave, F2-layer reflections or superrefraction arising from meteorological conditions.

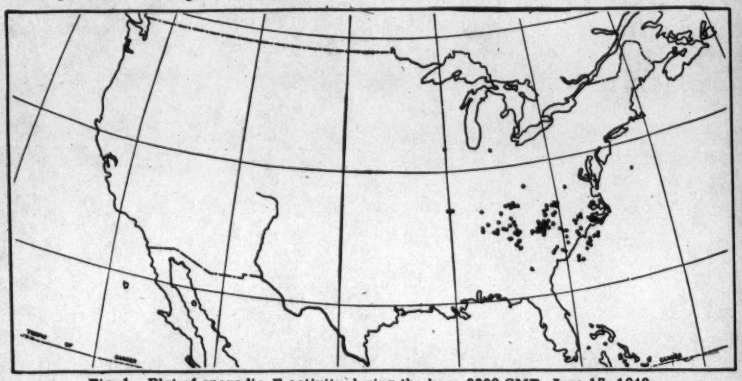


Fig. 1--Plot of sporadic-E activity during the hour 2300 GMT, June 17, 1949

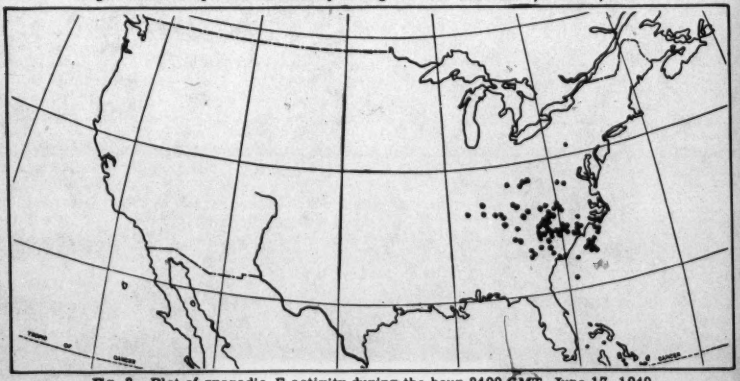


Fig. 2--Plot of sporadic-E activity during the hour 2400 GMT, June 17, 1949

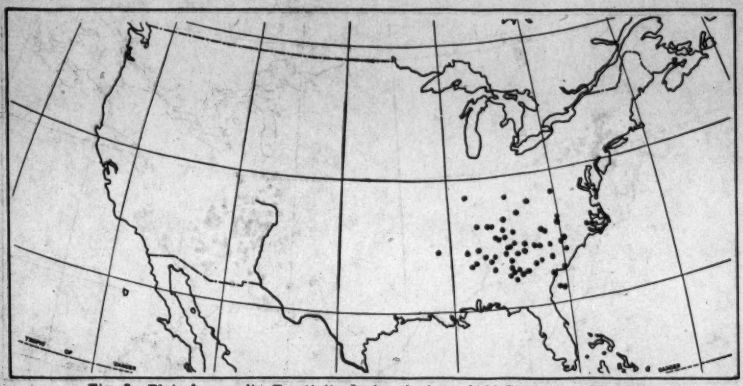


Fig. 3--Plot of sporadic-E activity during the hour 0100 GMT, June 18, 1949

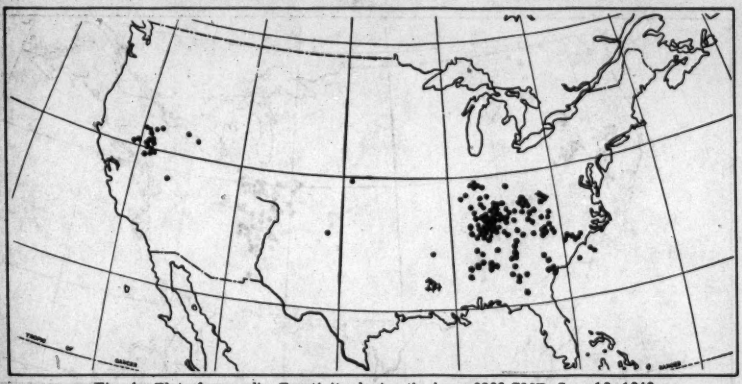


Fig. 4--Plot of sporadic-E activity during the hour 0200 GMT, June 18, 1949

After this procedure, the various observations were plotted upon maps of North America, as shown in Figures 1-7. Each dot represents the midpoint of a great circle path between two radio amateurs who were in touch with each other by means of Sporadic-E reflection, for which the path length did not exceed about 2200 km. All data for the hourly period centering on the indicated hour are included. If the path length exceeded this distance it was presumed that the transmission occurred by means of a double reflection from sporadic-E ionizations; in the latter case the midpoint of each half of the path is indicated by an X. The internal consistency between E_s determined by double- and single-hop propagation should be noted. The maps contain all radio contacts centering upon the hour indicated.

It appears that E_s covers a limited area of the continent and that this area changes both its shape and its position. Undoubtedly some observational bias is inherent in any data gathered on a cooperative basis. This bias arises from the irregular spacing of the radio amateurs over the continental and their different operating periods. Further, the scope of this method is somewhat restricted because it depends on oblique measurements made at only one frequency, 50 mc/s.

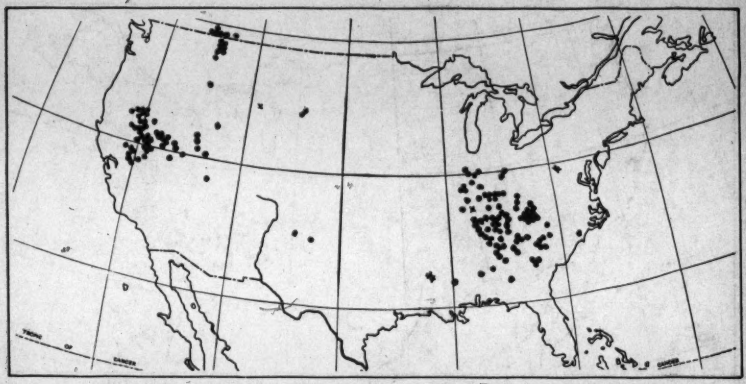


Fig. 5--Plot of sporadic-E activity during the hour 0300 GMT, June 18, 1949

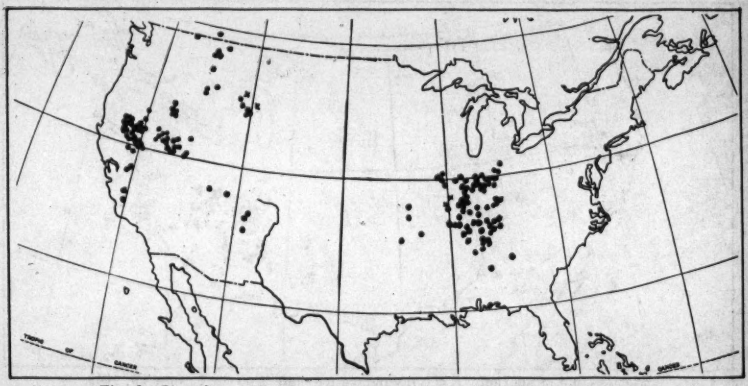


Fig. 6--Plot of sporadic-E activity during the hour 0400 GMT, June 18, 1949

Nonetheless, it is possible to draw some preliminary conclusions not only as to the rate of drift of sporadic E, but also as to the time of its appearance and disappearance.

Although the time of going "on the air" by each amateur is not known at this time, it is safe to assume that a sufficient number of radio amateurs were operating prior to 23^h00^m GMT to insure reports of E_s had it been observable at this frequency. Similar remarks apply to the hour immediately succeeding 05^h00^m GMT on the 18th. The abrupt onset of the numerous reports here summarized, then, indicates that sporadic E suddenly became observable at about 23^h00^m GMT over an area of several hundred thousand square km. This area, centered over southeastern United States, moves anticyclonically towards the southwest, thence towards the northwest. Had the area moved in from over the ocean, a gradual movement from the east would have been reported. The area became more extensive at 02^h00^m GMT when the northerly movement began, and finally disappeared at about 05^h00^m GMT. The average speed for the entire motion was about 175 km/hr. Whether this motion was uniform cannot be determined. Although the hourly dots summarizing the results on Figure 8 suggest acceleration and deceleration in the motion of E_s,

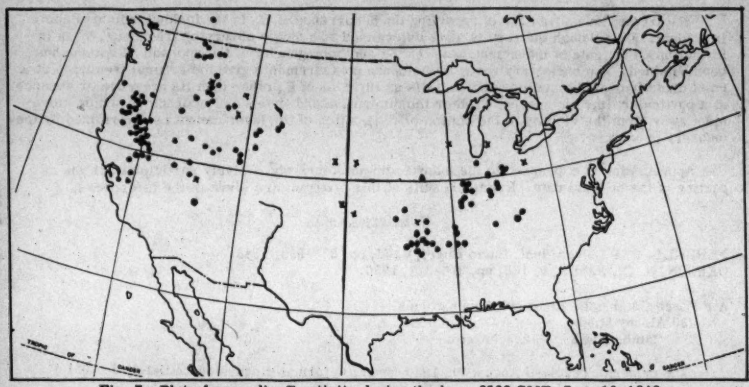


Fig. 7--Plot of sporadic-E activity during the hour 0500 GMT, June 18, 1949

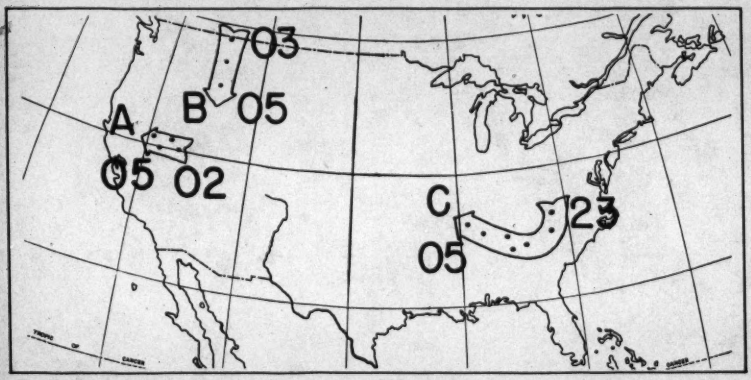


Fig. 8--Summary map indicating the movement of the "center of mass" of given sporadic-E areas

such results may be only accidental and introduced by (a) the geographical bias of the observers, and (b) the difficulty of explicitly determining a center for the E_s region. In this connection it should be noted that the mean velocity of the leading edge of the sporadic E area does not necessarily correspond to the mean velocity given above.

At 02^h00^m GMT a second E_s area (see A in Fig. 8) is observed over the western states. The sporadic E area moved slowly from the east at an average speed of about 95 km/hr. An hour later another small E_s area was reported from the western Canadian-United States border. This area moved towards the south at a speed of about 175 km/hr.

In each of the cases indicated above it should be noted that the disappearance of the E_s reflecting (or refracting) volume is preceded by a gradual dissipation. It seems that the E_s degenerates from a larger somewhat compact volume into smaller and somewhat separate cells. Such a mechanism would conform with the more erratic reflecting ability observed prior to disappearance of the E_s.

The tremendous advantage of reporting the occurrence of E_s in the fashion indicated above is evident. Even though the results were determined at a single observing frequency, much information on the rate of movement, size, extent and homogeneity of the sporadic E volume has been obtained. The customary vertical-incidence measurements give the critical frequency at a point directly over the station, but this tells us little about E_s other than its presence or absence at a particular time and place. Whether the diminution and absence of sporadic E denote movement away from the vicinity of the station or dissipation of the layer cannot be determined by the ordinary procedure.

Appreciation is expressed to the many radio amateurs who actively participated in the reporting of the original data. Earlier results of this program are given in the references.

References

FERRELL, O. P., Proc. Inst. Radio Engr., v. 36, pp. 879-880, 1948.
GERSON, N. C., Nature, v. 166, pp. 316-317, 1950.

Air Force Cambridge Research Laboratories,
230 Albany Street,
Cambridge 39, Massachusetts

(Manuscript received August 11, 1950; open for formal discussion until July 1, 1951.)

Transactions, American Geophysical Union Volume 32, Number 1 February 1951

SWASH AND SWASH MARK

K. O. Emery and J. F. Gale

(Contribution of Allan Hancock Foundation, No. 53)

Abstract--The time interval between swashes was found to be longer for gentle marine beaches than for steep ones owing to differing effectiveness of the beaches as wave filters. This relationship offers a possible means of determining the angle of beach slope from aerial reconnaissance. Swashes that cross the outcrop of the beach water table leave swash marks that are farther apart on gentle beaches than on steep ones. Three factors that control this spacing are the interference of swash on the beach, the width of beach exposed per unit time of tide fall, and the permeability of the beach.

Introduction--One of the most interesting and complex areas of the Earth is the boundary between land and sea: the shore zone. As waves enter shallow water they are transformed into breakers, or surf, which continue the water movement the rest of the way to shore. The forward momentum of the breakers carries some of the water up and across the foreshore of the beach until it sinks into the sand or flows back seaward in the interval before the arrival of the next breaker. This intermittent landward flow of water across the beach is termed swash, and its return to the sea is often referred to as backwash.

During each swash some water seeps downward through the sand to the level of complete saturation. Between swashes some of this water escapes by flowing laterally through the sand back toward the ocean. The top of the saturated zone is the water table, and the intersection of this water-table with the beach slope is marked by a broad line that separates the wet seaward side of the beach from the dry or slightly moist landward side. Water escaping through the surface of the seaward side of the beach forms a glassy film that gradually collects in rills draining seaward. The water table rises below the foreshore with flooding tide and sinks with ebbing tide [EMERY and FOSTER, 1948]. Smaller changes result from individual large swashes.

Swashes that cross the water table leave at their point of farthest advance a long thin ridge of sand: a swash mark. Because individual swashes cross only short sections of the beach, the swash marks are distributed in lines that are convex in the direction of wave movement. This characteristic is a criterion for determining the landward and the seaward side of ancient sand beaches [TWENHOFEL, 1932].

During the past ten years we have noted in various parts of the world that swash marks are present on practically all sandy marine beaches and on many lake beaches. Swash marks were observed to form only on the upper fairly dry part of the beaches, and never on the lower part that is covered by a thin glassy film of water [EMERY, 1945]. In addition, we have noted that swash marks are widely spaced on gently sloping beaches and closely spaced on steep beaches.

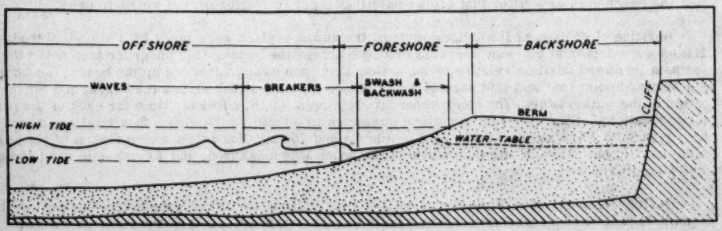


Fig. 1--Terminology

This latter characteristic, noted recently also by ROSALSKY [1949], is so prevalent that we believed quantitative data on the spacing and its cause should be secured. The investigation thus led to a study of the nature of the swash itself.

Swash

Methods of study--Slow-speed moving pictures of breakers approaching a beach and changing into swash were examined one frame at a time and the successive positions of the front of the breakers and swashes along a line normal to the beach were plotted (see Fig. 2). These and field observations show that the swash moves landward as a water mass several inches thick, the front of which is steep and usually marked by a line of foam. During this stage its appearance is something like that of a small-scale tidal bore. The retreat of a swash from the beach is much different, however, because it retreats by becoming progressively thinner without much change in position

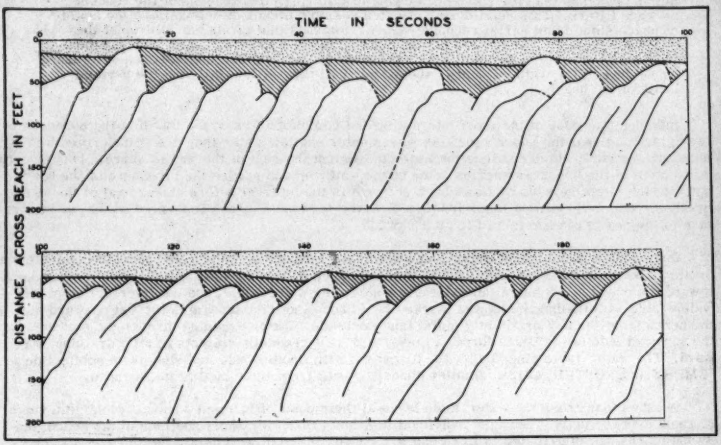


Fig. 2--Changing positions of breakers and swash as read from frames of motion pictures; dotted area is dry beach sand; lined area is saturated sand

of the swash front until all the water is gone. Figure 2, therefore, shows the changing position of the advancing breaker as a solid line that continues as swash across the beach. The changing position of the retreating backwash is marked by a dashed line to indicate uncertainty. The photographic record shows clearly the absorption or filtering out of small breakers before they reach the beach to become swash, and the passing of small swashes by large ones. Thus, it is evident that the beach acts as a filter that allows only the larger or longer period waves to pass.

Because of equipment limitations most of the swash studies were made by a visual method. Stakes were driven at ten-foot intervals in a line across the beach. One observer then noted the farthest landward position relative to the stakes that each swash advanced up the beach, the farthest seaward point that was laid bare of water before the next swash struck the beach, and the position of the water table. The other observer, holding a watch, noted the time for each of the previous notations. Each set of observations lasted ten to 50 min. Altogether, they total about ten hours, include 23 series on 15 different beaches along 250 mi of coast, and cover most of the possible conditions. At each site the profile of the beach was measured, and a composite sand sample was collected.

During one of the sets of measurements, a simultaneous record of wave height and period at a point 1100 ft offshore was obtained by a bottom-mounted, pressure-type wave recorder. The distance and depth of water between the wave recorder and the beach was such that the waves required about 63 sec to cross it. For this record we are indebted to R. S. Arthur of Scripps

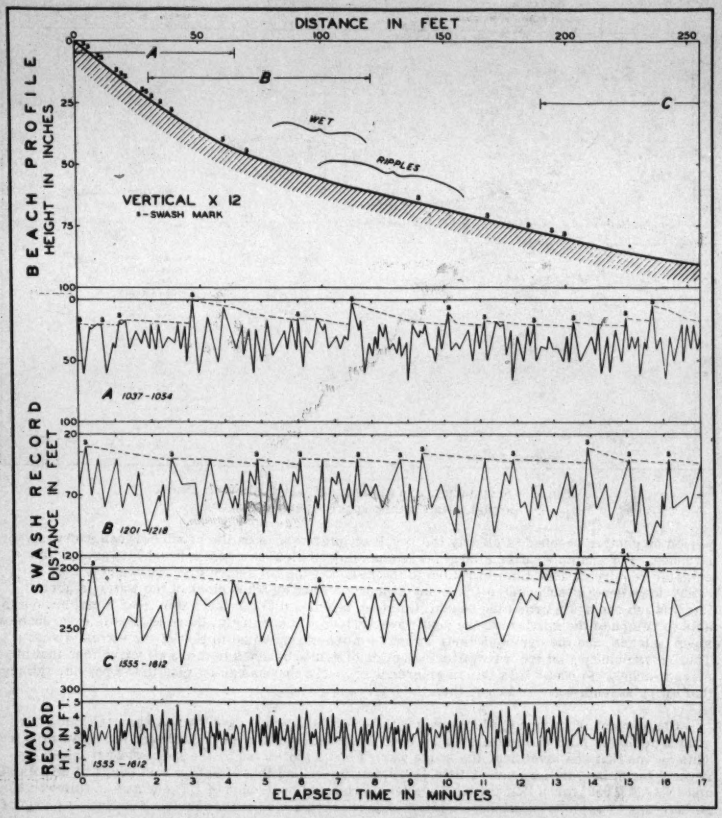


Fig. 3--Examples of swash record obtained over three parts of a concave beach at different stages of tide; the wave record was made concurrently with swash record (C) but is probably characteristic of the whole day

Institution of Oceanography. At other observation sites only the period of the waves at sea could be obtained.

Results--When plotted, the observations yield a jagged curve (see Fig. 3) that shows the changing position of the boundary between the subaqeous and the subaerial parts of the beach. The line of outcrop of the water-table slowly shifts seaward but is intermittently moved landward again when a swash runs farther up the beach than usual.

Analyses of the swash records from the various beaches showed that the period of the swash was in all instances greater than that of the waves before they reached the beach, and that the gentler the beach, the longer was the period of the swash (see Fig. 4). The lengthening of the

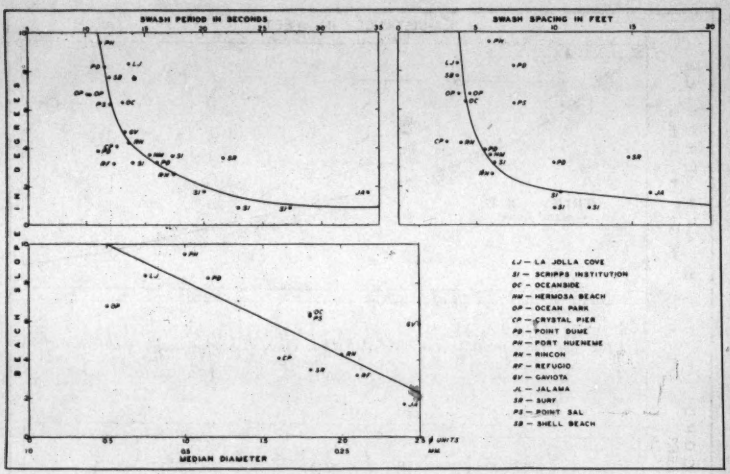


Fig. 4--Summary of relationship of beach slope to swash period, swash mark spacing, and grain size

period on gentler beaches is clearly the result of interference on the beach between successive swashes. For example, after a large swash has moved high up a gentle beach, its great volume of water requires a long time to return to the sea. During its return this backwash is able to break down several successive advancing swashes. Finally, when most of the water is gone, a later swash can again cross the beach. On steep beaches most of the water from a given wave is able to return to the sea before the next wave arrives. Accordingly, there is less interference on steep beaches, and the period of their swash is more nearly equal to that of the waves at sea. Thus, it is evident that the wave filtering action of gentle beaches is more effective than that of steep beaches. Perhaps it is this interference of swash that has given rise to the popular fallacy that every seventh wave is larger than the intervening ones.

Comparison of record C of Figure 3 with the simultaneous wave record shows that shortly after a period of high waves the area covered by swash was displaced landward for a few minutes. This means that sea level near the shore was raised a foot or so by the shoreward transport of several incoming large waves. MUNK [1949] has described this effect as surf beat and SHEPARD and INMAN [1950] found that the high sea level produced by groups of large waves is followed by an increase in velocity of offshore current that reaches a maximum during a subsequent group of small waves. Thus, interference of backwash appears to form surf beat that in turn furnishes the head of water for rip tides (rip currents).

Swash marks

Origin--As a swash advances across a beach its front is marked by a rather obvious line of foam, but close observation shows that the foam is sometimes preceded by a thin wedge of clear water. While this wedge is crossing the saturated seaward side of the beach it carries little or no sand, though the water behind it moves sand in suspension and by traction. When the swash passes the water-table outcrop, however, its front edge picks up and carries some sand by flotation. This is evidently the result of a rising water level and the surface tension of the water [EVANS, 1938; EMERY, 1945]. The floating sand is dropped if the grains enter the zone of turbulent movement in the foam zone and become completely wetted. New sand is picked up to replace that which is lost. Finally, when the swash reaches the point of greatest advance and begins its seaward retreat, all the water in the wedge at the very front of the swash sinks into the beach, depositing its load of sand grains as a swash mark. If the point of farthest advance were still

within the completely saturated side of the beach, the water of the wedge would have been unable to float much sand and even that small quantity would be carried back seaward again because the water in the swash is unable to seep into the already saturated sand. Thus, we find that swash marks are formed only on the dry upper (landward) side of the beach, never on the lower (seaward) side below the outcrop of the water table.

Commonly, the swash marks contain a higher than normal percentage of angular grains such as mica flakes and shell fragments and of light grains such as small hollow shells and organic debris. If the beach consists only of very coarse sand, few of the grains are picked up, probably because of their weight and inertia, so swash marks are relatively rare on such beaches. Under some conditions, the foam itself carries sand that gives it a dirty appearance. On retreat of the swash some of the foam is stranded and after evaporation of the foam a broad zone of sand is left to mark the point of farthest advance of the swash.

Swash marks are known from several ancient beach deposits, though the latter are not very common [FAIRCHILD, 1901; CLARKE, 1918]. Possibly, their preservation is made possible chiefly by the formation of a thin crust of sand cemented by salt deposited during evaporation of interstitial water brought up by capillarity from the water table [EMERY and FOSTER, 1948].

Spacing--Several hundred qualitative observations showed us that the average spacing of swash marks ranges from between ten and 20 ft for gentle beaches to less than one foot for steep beaches. Quantitative measurements of swash spacing were obtained from the swash record (see Fig. 2 and 3). After a swash crossed the water-table and left a swash mark, a later swash might also cross the water table but not go as far up the beach as the first wave. Its swash mark would then be located between the first one and the outcrop of the water table. By averaging the distances between such successive swash marks we obtained an average spacing for each beach. This figure approximates the average spacing between swash marks of the whole series left on the beach between the high and low tide lines.

Because of less interference, more swashes cross steep beaches than gentle ones, so more are available for making swash marks. If the tide range is the same at both sites, the falling tide must expose a greater width of gentle beach than of steep beach per unit time. Thus, even if swashes had the same period on both gentle and steep beaches, the swash marks would be farther apart on gentle than on steep beaches. The generally coarser grain size of steep beaches permits faster draining of water and lowering of the water table between swashes than for gentle beaches. As swash marks form only on the unsaturated parts of the beaches, there are clearly more opportunities for swash marks to form on steep than on gentle beaches.

In summary, three factors permit closer spacing of swash marks on steep than on gentle beaches: (a) less wave interference on steep beaches; (b) less width of steep beach exposed per unit time by the falling tide; and (c) faster fall of water table in steep beaches.

Significance--The presence of swash marks in ancient sandstones has in the past been used as an indicator of intertidal beach environment, and their convexity as an index of the former position of land and sea. We may perhaps now use the spacing of swash marks as a criterion of beach slope to supplement the use of grain-size for the same purpose (see Fig. 4). Conceivably also, if one measured the total width of an ancient beach that is covered by swash marks, one could determine the ancient tide range.

The swash measurements show that the swash period is closely related to the beach slope. The data presented in Figure 4 suggest that swash period could well be taken as an index of beach slope. As swash period can be obtained from moving pictures taken from an aircraft at high altitude, it offers a method of estimating beach slope from aerial reconnaissance, and, thus, it may prove to be of some value in planning amphibious landing operations. Further work that takes into account the period of the waves or swell at sea, the width of the swash zone, and other as yet unknown factors, would probably show a better relationship between swash period and beach slope.

References

CLARKE, J. M., Strand and undertow markings of upper Devonian time as indications of the prevailing climate, N. Y. State Mus. Bull., v. 196, pp. 199-239, 1918.

EMERY, K. O., Transportation of marine beach sand by flotation, J. Sed. Petr., v. 15, pp. 84-87, 1945.

EMERY, K. O., and J. F. FOSTER, Water tables in marine beaches, J. Mar. Res., v. 7, pp. 644-653, 1948.

EVANS O. F., Floating sand in the formation of swash marks, J. Sed. Petr., v. 8, p. 71, 1938.
FAIRCHILD, H. L., Beach structure in Medina sandstone, Amer. Geol., v. 28, pp. 9-14, 1901.
MUNK, W. H., Surf beats, Trans. Amer. Geophys. Union, v. 30, pp. 849-854, 1949.
ROSALSKY, M. B., A study of minor beach features at Fire Island, Long Island, New York, Trans. N. Y. Acad. Sci., ser 2, v. 12, pp. 9-16, 1949.
SHEPARD, F. P., and D. L. INMAN, Nearshore water circulation related to bottom topography and wave refraction, Trans. Amer. Geophys. Union, v. 31, pp. 196-212, 1950.
TWENHOFEL, W. H., Treatise on sedimentation, Williams and Wilkins, Baltimore, 2nd ed., pp. 669-670, 1932.

University of Southern California,
Los Angeles 7, California

(Communicated manuscript received July 18, 1950; open for formal discussion until July 1, 1951.)

Transactions, American Geophysical Union Volume 32, Number 1 February 1951

TOTAL REFLECTION OF SURFACE WAVES BY DEEP WATER

John D. Isaacs, E. Allan Williams, and Carl Eckart

(Contribution from the Scripps Institution of Oceanography, New Series, No. 498)

Abstract--A mechanism is described by which surface gravity waves generated in shallow water may be totally reflected from deep water. The mechanism by which waves generated in deep water may be "captured" is also discussed.

Introduction--It has been the intuitive feeling of those engaged in the studies of shoreline processes that some mechanism must exist by which the surf zone can resonate to the fluctuations in the height of the wind waves and swell. These fluctuations have been observed to produce variations in the average height of the water line, and recently have been described and named "surf beat" [MUNK, 1949]. The phenomenon which has required the assumption of a resonant system is that the fluctuations in average water level bear no simple relationship to the momentary height of the wave groups and are much affected by the periodicity of their occurrence. The surging of the surf zone displays a beat phenomenon, successively being in and out of phase with the incoming groups. This beating frequently results in a period of exaggerated surging followed by a period of low surging, both coinciding with the arrival of similar groups of high waves. Also there is sometimes no conspicuous surging, and on other occasions almost continuous surging. It is suggested that these differences depend upon the relation of the resonant period to that of the incoming waves.

To the observer these have always suggested the forced oscillation of a resonant system, but until now no mechanism has been described that would explain resonant periods of the water over a sloping bottom of infinite seaward extent. Such a mechanism is suggested below. This mechanism also has other important applications to the problems of shoreline processes.

Total reflection of surface waves by deep water--Consider a straight beach with parallel contours, so that the phase velocity C of surface waves is a function only of the distance, y, measured perpendicular to the shore. Then, if α is the angle between a ray and the y-axis, Snell's law states that $\sin \alpha / C$ = constant, along the ray. If C_0 is the deep-water velocity, and α_0 the angle of approach from deep water, the equation becomes

$$\sin \alpha = (C/C_0) \sin \alpha_0$$

where α and C refer to some value of y.

Consider how α varies with α_0. The maximum value of $\sin \alpha_0$ is unity, and this occurs for waves that, in deep water, are propagated parallel to the beach, that is, glancing incidence. For such waves, $\alpha = \alpha_c$ where the critical angle α_c is given by

$$\sin \alpha_c = C/C_0$$

Thus, all waves generated at sea pass across the contour at distance y at an angle less than this critical value.

However, waves may be generated in shallow water with angles greater than α_c. Such waves will not be able to reach deep water, but will be totally reflected, at that depth where the wave velocity is C_m, given by

$$C_m = C/\sin \alpha, \quad \alpha > \alpha_c$$

This is illustrated in Figure 1, which shows how a ray that leaves shallow water at an angle greater than α_c is curved and returns to the beach after having been deflected parallel to the beach at the distance y_m from shore.

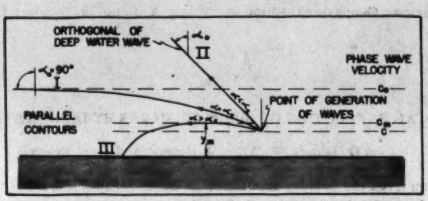


Fig. 1--Waves generated in shallow water and refracted over parallel straight contours; I, orthogonal of wave generated in shallow water with the critical angle α_c enters deep water at an angle α_0 of 90°; II, orthogonal with $\alpha < \alpha_c$; III, wave generated in shallow water with angle $\alpha > \alpha_c$ is reflected from deep water at depth y_m

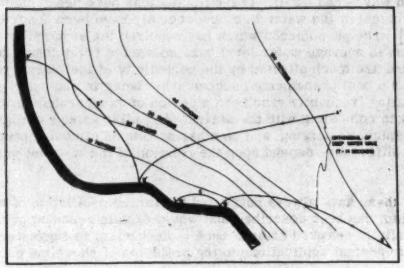


Fig. 2--Total reflection from deep water occurs at C or C′ for waves generated in deep water and reflected from a curved beach

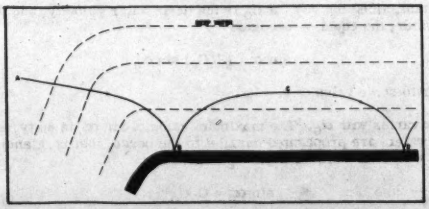


Fig. 3--Deep water wave, which enters shallow water over curved ontours and crosses straight contours at an angle greater than the critical angle, is reflected from the shore at B and totally reflected from deep water at C

Consequently one may expect the formation of standing waves, reflected alternately from the beach and from deeper water. These standing waves will have natural periods, much as the standing waves in an organ pipe are responsible for its resonance. However, in general the natural frequencies of a sloping beach will not be integral multiples of a fundamental, as is the case with an organ pipe or stretched string. Nonetheless, they will be resonance frequencies, so that a relatively small exciting force of proper period can produce relatively large effects.

The process of total reflection from deep water can also occur on curved beaches, for waves

generated in deep water and reflected from the beach. This is shown in Figures 2 and 3. Waves generated at sea come into shore along the curved ray AB, are reflected by the beach at B, and proceed along the ray BCD, being totally reflected at C.

The reflection at B is complicated by surf and breaker phenomena for waves of ordinary periods and heights, so that the coefficient of reflection at B may be very small. For very low amplitude waves, however, the coefficient of reflection at the beach may be nearly unity. This low amplitude may be caused by the initial refraction along the ray AB. Breakwaters and jetties may also reflect waves in such a manner that they are totally reflected and returned to the beach from deep water.

Another topographic situation that may make for total reflection from deep water is a bar covered by shallow water. Waves generated over the bar will be reflected from the deep water on both sides. Similarly wind waves generated in a shallow sea, such as the Bering Sea, may be reflected from adjacent deeper seas. Total reflection can also occur from regions of variable current.

Generation of waves in shallow water--The generation of wind waves in shallow water has already been mentioned but there are other possibilities.

The generation of waves with periods of several minutes (surf beat) by groups of breakers has been discussed by MUNK [1949]. Whether such waves move out to sea, or are totally reflected and return to the beach, depends on the angle of their front to the bottom contours. This question has been investigated, using methods similar to those employed by STONELEY [1935] in treating the refraction of groups of incoming waves.

If a group of long-crested waves advances from deep to shallow water, the effect of refraction will be to convert it into a group of short-crested waves, advancing toward shore in an echelon formation (see Fig. 4). The diagram is, of course, exaggerated, since even deep water waves do not have crests that are indefinitely long. A detailed investigation of several possible cases of groups of long-crested waves approaching shore at an angle, shows that the surf-beat wave generated by an echelon of waves will be totally reflected by the offshore waters. Hence one may also expect the surf beat to consist of standing waves, reflected alternately from the beach and from deep water, as was suggested above.

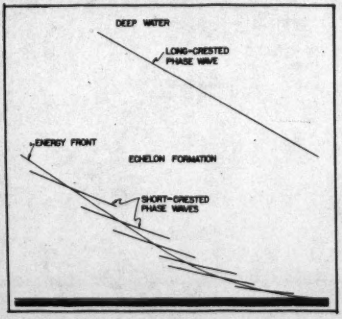


Fig. 4--Echelon formation of short-crested waves produced by group refraction

The seiches revealed by tide records at exposed locations and sometimes attributed to the resonance of "offshore basins" and similar topographic features are probably merely an example of the multiple reflection of long period waves between the shore and the deeper water, and may be only slightly affected by the bottom topography in deeper water.

This effect, combined with reflections from headlands, very likely accounts for the surging of open harbors like Monterey Harbor. The force exciting these surges may be the surf beat on adjacent beaches.

There have been observed very high amplitude surges with periods of several minutes on perfectly open coasts [MUNK, 1949]. The forces causing these surges are not obvious, although they must be connected with heavy seas. As a working hypothesis, one may assume that the resonance due to the sloping bottom is an important factor.

Acknowledgment--This work represents results of research carried out for the Beach Erosion Board, Corps of Engineers, Department of the Army, Contract W-49-055-eng-3.

References

MUNK, W. H., Surf beat, Trans. Amer. Geophys. Union, v. 30, pp. 849-854, 1949.
STONELEY, R., The refraction of a wave group, Proc. Cambridge Phil. Soc., v. 31, pp. 360-367, 1935.

Scripps Institution of Oceanography (J.D.I. and C.E.),
La Jolla, California

University of California (E.A.W.),
Santa Barbara College,
Santa Barbara, California

(Communicated manuscript received July 24, 1950; open for formal discussion until July 1, 1951.)

Transactions, American Geophysical Union Volume 32, Number 1 February 1951

THE ADIABATIC GRADIENT IN THE MANTLE

Jean Verhoogen

Abstract--A method is suggested by which the adiabatic gradient at any depth in the mantle can be determined from seismic data. The average gradient from 200 to 2600 km depth is found to be approximately 1.7×10^{-4} T_{200} deg/km, where T_{200} is the temperature at 200 km depth. This average gradient agrees well with Benfield's recent estimate.

BENFIELD [1950] has recently emphasized the importance of the adiabatic gradient in determining the initial temperature distribution caused by self compression in a cold accreting Earth. A knowledge of this gradient is also necessary to determine the condition for stability with respect to convection under vertical temperature gradients in the mantle. As is well known, the adiabatic gradient may be written as

$$dT/dP = \alpha T/\rho c_p$$

where T is temperature, P is pressure, α is the coefficient of thermal expansion, ρ is the density, and c_p is the specific heat at constant pressure. If hydrostatic equilibrium is assumed, the pressure varies with depth h as $dP = g\rho dh$, so that

$$d \log_e T/dh = \alpha g/c_p$$

from which the temperature T_h at any depth h may be computed as a function of the temperature at any assigned depth if the ratio α/c_p is known at all depths (g, the acceleration of gravity, will be taken as constant in the mantle). Benfield has taken $c_p = 1 \times 10^7$ ergs/gm deg and estimates, admittedly from very scanty data, an average value $\alpha = 1.5 \times 10^{-5}$/deg throughout the mantle and core. The purpose of this paper is to show that the ratio α/c_p at any depth may be determined with sufficient accuracy from seismic data.

It has been shown by DEBYE [1912], BORN and BOLLNOW [1927], BRILLOUIN [1938], GRUNEISEN [1926], and others, that the thermal expansion of a solid must be related to its compressibility and specific heat [see for instance SLATER, 1939, Chap. 13 and 14]. The common basis of these theories is similar to the statistical theory of specific heats in which the oscillatory motion of the particles of a solid is represented by superposing a large number of elastic waves of variable frequency traveling back and forth through the solid with the well-known characteristic velocities v_l, v_{tr} of elastic waves. The frequency of these waves, longitudinal and transverse, ranges from zero to an upper limit resulting from the condition that one-half the wave length cannot be less than the distance between neighboring particles. If N is the number of particles in volume V, the limiting frequencies for longitudial and transversal waves are given respectively by the well-known relations

$$\nu_l = v_l(3N/4\pi V)^{1/3} \quad , \quad \nu_{tr} = v_{tr}(3N/4\pi V)^{1/3}$$

Introducing the characteristic Debye temperatures $\theta_l = h/k\nu_l$ and $\theta_{tr} = (h/k)\nu_{tr}$ where h and k are respectively Planck's and Boltzmann's constants, BRILLOUIN [1938, p. 336] writes the internal, or "thermal" pressure p_i corresponding to the radiation pressure of these elastic waves in the form

$$p_i = -(U_l/\theta_l)\partial\theta_l/\partial V - 2(U_{tr}/\theta_{tr})\partial\theta_{tr}/\partial V$$

where U_l and U_{tr} are respectively the energies associated with the longitudinal and transverse vibrations; the factor 2 takes care of the fact that there are really two types of transverse elastic waves whose velocities become equal only in the case of isotropic bodies. A simple transformation then leads to

$$p_i = (U_l/V)\,[(\rho/v_l)\partial v_l/\partial\rho + 1/3] + 2(U_{tr}/V)\,[(\rho/v_{tr})\partial v_{tr}/\partial\rho + 1/3]$$

Table 1--Values of the terms for the material forming the mantle

Depth	$(\rho/v_\ell)\partial v_\ell/\partial\rho$	$(\rho/v_{tr})\partial v_{tr}/\partial\rho$
km		
200	1.31	1.11
600	1.11	1.08
1000	1.06	1.02
1400	1.02	0.92
1800	0.97	0.85
2200	0.92	0.76
2600	0.85	0.71

The values of the terms $(\rho/v_\ell)\partial v_\ell/\partial\rho$ and $(\rho/v_{tr})\partial v_{tr}/\partial\rho$ for the material forming the mantle may be determined from BULLEN'S [1947] data and are tabulated in Table 1.

It simplifies matters greatly to take at each depth an average value m for these two quantities. We have then, simply

$$p_i = (U/V)(m + 1/3)$$

where U is the total energy of the solid.

Now a relative change in volume $dV/V = \alpha dT$ resulting from a change in temperature dT at constant external pressure P may be expressed as resulting from a change in the internal pressure p_i acting on a body with compressibility χ

$$dV/V = \alpha dT = \chi dp_i$$

Hence

$$\alpha = \chi(dp_i/dT)_P$$

By standard manipulations we find $(\partial U/\partial T)_P = C_P - PV\alpha$ where C_P is the specific heat per mole, so that

$$\alpha/C_P = 1/[U + PV + V/\chi(m + 1/3)]$$

At extremely high temperature U would tend to the limiting value 3nRT, where R is the gas constant and n is the number of atoms per molecule. For olivine Mg_2SiO_4 n = 7, so that under conditions prevailing at the bottom of the mantle, where $P = 1.37 \times 10^{12}$ dynes/cm^2 and V, the molar volume of olivine, is 140/5.6 = 25 cm^3, PV is of the order of 20 U for temperatures of the order of 10^3 degrees. Neglecting U, and reverting to the specific heat per gram, we have finally

$$\alpha/c_p = \rho/[P + 1/(m + 1/3)]$$

where all the quantities on the right-hand side may be obtained from Bullen's data and Table 1. The values of α/c_p and $T_h/T_{200} = \exp\left[\int_{200}^{h} g(\alpha/c_p)dh\right]$ are listed in Table 2, where, for the sake of comparison, an approximate value of α/c_p for olivine under normal conditions is given. It should be emphasized, however, that the results in Table 2 are independent of the chemical nature of the material forming the mantle, since the quantities to enter into the equation are all derived from seismic data.

Table 2--Values of α/c_p and T_h/T_{200}

Depth	$\alpha/c_p \times 10^{12}$	T_h/T_{200}
km	gm/ergs	
0	(4.2)	..
200	3.61	1.0
600	2.05	1.11
1000	1.54	1.19
1400	1.27	1.25
1800	1.08	1.31
2200	0.92	1.37
2600	0.81	1.41

From the results in Table 2 it is easily found that the average adiabatic gradient in the mantle between the depths of 200 and 2600 km is $1.7 \times 10^{-4}\ T_{200}$ deg/km. If we set arbitrarily $T_{200} = 1000°$K, this average gradient becomes 0.17 deg/km, somewhat less than the usually accepted value 0.4 deg/km. The corresponding average value of α/c_p is 1.43×10^{-12}, in close agreement with Benfield's estimate (1.5×10^{-12}). Due to the neglect of certain terms, and to the use of an average value m for the two terms $d \log_e v_\ell / d \log_e \rho$ and $d \log_e v_{tr} / d \log_e \rho$, it is not expected that the values of α/c_p listed in Table 2 could be very accurate; they are probably somewhat too large, particularly above 1000 km depth. It is believed, however, that the present calculations offer perhaps a more rational basis for evaluating the adiabatic gradient at depth than extrapolation from extremely meagre experimental data at relatively low pressure.

References

BENFIELD, A. E., Temperature in an accreting Earth, Trans. Amer. Geophys. Union, v. 31, pp. 53-57, 1950.
BORN, M., and O. F. BOLLNOW, Der Aufbau der festen Materie, Handbuch d. Physik, Springer, Berlin, v. 24, pp. 370-465, 1927.
BRILLOUIN, L., Les Tenseurs en Mecanique et en Elasticité, Masson, Paris, 1938.
BULLEN, K. E., An introduction to the theory of seismology, Cambridge University Press, 1947.
DEBYE, P., Ann. d. Physik, v. 39, p. 789, 1912.
GRUNEISEN, E., Zustand des festen Körpers, Handbuch d. Physik, Springer, Berlin, v. 10, pp. 1-59, 1926.
SLATER, J. C., Introduction to Chemical Physics, McGraw-Hill, New York, 1939.

Department of Geological Sciences,
University of California,
Berkeley 4, California

(Communicated manuscript received June 14, 1950; open for formal discussion until July 1, 1951.)

Transactions, American Geophysical Union Volume 32, Number 1 February 1951

A FURTHER INVESTIGATION OF THE RADIOACTIVITY OF THE ROUND LAKE AND ELZEVIR BATHOLITHS

H. A. Slack and K. Whitham

Abstract--A field gamma-ray counter suitable for measuring weak radioactive sources has been designed and built. It was mounted in a truck and used to investigate the distribution of radioactivity over two batholiths in the Pre-Cambrian Shield. The distribution of radioactivity had previously been investigated by determining the alpha ray emission from prepared hand specimens.

The instrument is described. By recording the anticoincident counts between two rows of Geiger tubes, approximately 70 per cent of the cosmic-ray background was eliminated, making possible more precise and rapid determination over weakly radioactive rocks. Since gamma radiation was recorded sampling errors were considerably reduced. The instrument was calibrated using artificially prepared rock bodies.

Diagrams are presented for the two batholiths and for a suite of freshly exposed Pre-Cambrian rocks showing the readings obtained in this way compared with those obtained by the alpha counting method. The uncertainties in interpretation of field results due to the presence of potassium in rocks are discussed.

Introduction--The method used in this laboratory for determining the radioactivity of weakly radioactive rocks by counting the rate of alpha ray emission from prepared hand specimens has been shown to be susceptible to serious sampling uncertainties [KEEVIL and Others, 1943]. Although the method is precise for a given specimen, small hand specimens may not be representative of the rock as a whole. The method requires grinding and preparation of the specimens and long counting periods and delays the collection of much needed radioactive data.

In order to shorten the time factor and to obtain more representative sample counts of rocks as units, it was believed that measurements in the field would be more desirable than laboratory counts on single hand specimens. It was also decided that gamma-ray counts rather than alpha-ray counts would be more representative for surface outcrops or would minimize the effects of overburden on emission rates. Because the ordinary type of portable geiger counter is not sufficiently sensitive to deal quantitatively with the weak radioactivity of the common rocks and the cosmic-ray background, it was necessary to construct an apparatus which would appreciably decrease the background count. In the apparatus described, the background count was reduced by recording the anticoincidence counts between two trays of geiger tubes one placed vertically above the other. The higher energy of cosmic ray particles allows an appreciable fraction of them to fire one or more geiger tubes in each of the trays whereas a gamma ray from rocks is sufficiently energetic to fire a tube in only the lower tray. The first instrument was operated in the field during the summer of 1949. A three-fold increase in sensitivity was obtained and counts representing the radioactivity of some ten cubic feet of rock. An investigation of two batholiths whose radioactivity had previously been studied was suggested.

Description of instrument--Figure 1 shows a block diagram of the apparatus used. The detector unit contained the two trays of geiger tubes, six in the upper tray and five in the lower tray. These were commercial gamma tubes 18 inches long and one inch in diameter with a 0.020-inch brass wall. Their individual plateaus were measured in the laboratory and the 11 tubes used were operated at +1000 volts. This corresponds to approximately one-third of the way along the plateau. The efficiency claimed by the manufacturers for cosmic-ray detection was ≥ 99.5 per cent and the efficiency for 1.2 mev gamma radiation from Co^{60} was measured as 1.6 per cent. Pulses obtained from them were fed by two cathode followers through a 100-ft cable to the two inputs of the anticoincidence mixer. This mixer was adapted from the Mk. 1 Model 2 anticoincidence mixer currently being used at Chalk River for cosmic ray studies. The monostable flip-flops, one corresponding to each channel, produced standard negative pulses, those produced from geiger pulses in the bottom tray were inverted and fed to the no. 1 grid of a 6AS7 mixer tube while the output corresponding to geiger pulses in the top tray was fed directly to the no. 3 grid of the same tube. Under the operating conditions used, simultaneous pulses in the two channels gave zero output, a

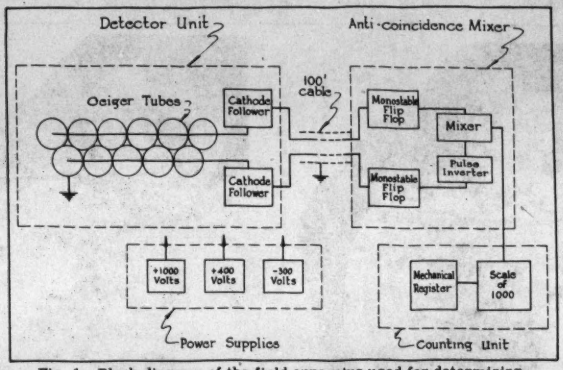


Fig. 1--Block diagram of the field apparatus used for determining the radioactivity of weakly active rock bodies

geiger pulse produced in the top tray of six tubes gave zero output whereas one produced in the bottom tray of five tubes gave a negative output pulse which was fed to a scaling unit. In field operation the detector unit was placed upon the rock outcrop being investigated. The anticoincidence mixer, counting unit and power supplies operated from storage batteries were contained in a truck. Measurements were limited to outcrops within 100 ft of passable roads.

Calibration on instruments--The reduction in cosmic-ray background was measured in a wooden boat over Lake Ontario and effects due to radioactive sources in the laboratory were eliminated. The best value obtained for background counting rate was 1060 counts per five minutes compared with 3710 counts per five minutes when it was not in anticoincidence. This represents a decrease in background counting rate of some 70 per cent with a corresponding increase in sensitivity. This background counting rate was independently confirmed by the fact that during the field work minimum values obtained over a period of two months on very weakly active rocks, such as limestones containing no potassium, were 1055 ± 30 counts per five minutes. Experiments in the laboratory with two channel arrays arranged in different geometrical positions showed that even completely surrounding the register tubes with non-register channel tubes produced very small changes (less than a few per cent) in the efficiency for cosmic ray elimination. Thus the simple geometrical arrangement used was near an optimum. It was also shown that no appreciable change in background was recorded upon tilting the detecting unit through small angles ($<30°$). No correction need therefore be made for slightly inclined outcrops.

For a rock containing U micrograms of uranium per gram of rock, Th micrograms of thorium per gram of rock and K per cent of potassium, calibration experiments showed, that after correcting for background, the signal counting rate per second was $C = 0.72\ U + 0.36\ Th + 2.2\ K$.

These experiments were carried out on artificial rock bodies obtained by mixing known amounts of uranium and thorium, in radioactive equilibrium, with known weights of sand. The estimated uncertainties in these constants are one, five, and ten per cent respectively and primarily arise in the case of uranium and thorium because of uncertainties in the calibration of the radioactive concentrates used. Assuming a semi-infinite rock, integrating for the count produced by rays of any one energy upon a certain counting area and finally summing up for the different energies present, it can be shown that

$$C = (A\rho/4) \sum_i (N_i\, \epsilon_i/\mu_i)$$

where A = effective counting area
ρ = average density of rock
N_i = rate of gamma ray emission/sec for rays of any energy E_i per unit mass of rock
μ_i = absorption coefficient for rays of energy E_i in rock
ϵ_i = per cent efficiency of Geiger tubes for rays of energy E_i
C = observed counting rate

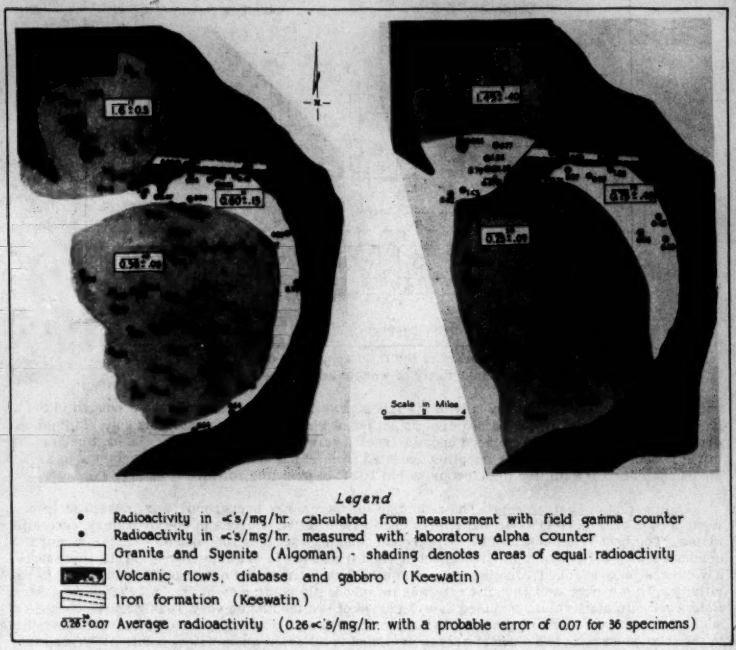

Scale in Miles
Legend
Radioactivity in ∝'s/mg/hr. calculated from measurement with field gamma counter
Radioactivity in ∝'s/mg/hr. measured with laboratory alpha counter
Granite and Syenite (Algoman) - shading denotes areas of equal radioactivity
Volcanic flows, diabase and gabbro (Keewatin)
Iron formation (Keewatin)
0.26±0.07 Average radioactivity (0.26 ∝'s/mg/hr. with a probable error of 0.07 for 36 specimens)

Fig. 2--Location of radioactive determinations on and around the Round Lake Batholith obtained in the one case with the laboratory alpha counter and in the other with the field gamma counter; all values are expressed in alpha particles emitted per milligram of rock per hour (α/mg/hr)

Calculations based on the summation of this series for uranium and its daughter products and thorium and its daughter products agreed with the experimental values within the large limits of uncertainty of the summation. The potassium value is a calculated one based upon

N_1 = 3.66 ± 0.3 gamma quanta/sec/gm potassium [SAWYER and WIEDENBECK, 1949]

ϵ_1 = (1.9 ± 0.05) pct [BROWN, 1948, p. 51]

μ_1/ρ = 0.045 ± 2 per cent [HESS, 1947]

It can be readily shown that the alpha activity in α/mg/hr for such a rock is given by

$$a = 0.34\ U + 0.095\ Th$$

and the radiogenic heat production is best expressed as H cals/gm/m y where

$$H = 0.72\ U + 0.20\ Th + 0.235\ K\ \text{[BULLARD, 1942]}$$

The figure for K of 23.5 ± 2.5 cal/gm of K/m y is a recent estimate in this laboratory, Assuming $Th/U = r_1 = 3.2$ [KEEVIL, 1944], and $K/U = r_2 = 1.4$ [KEEVIL, 1943], H = (2.60 ± 0.05)a, and a = (0.13 ± 7 pct)C.

While H is relatively uncritical to r_1, it is critically dependent on r_2. For all values of r_2

Fig. 3--Location of radioactive determinations on and around the Elzevir batholith obtained with the field gamma counter; all values are expressed in alpha particales emitted per milligram of rock per hour (∝/mg/hr)

from 1 to 2 a variation in r_1 from 3 to 4 changes H by less than seven per cent whereas for $r_1 = 3.2$ as r_2 changes from 1 to 2, H changes by 25 per cent. It is obvious that a further study must be made of the variation of the ratio K/U in rocks.

Discussion of results for Round Lake Batholith--Ninety determinations were made on the Round Lake Batholith and the surrounding country rock situated approximately 16 mi south of Kirkland Lake in northwestern Ontario (see Map 1934a of the Abitibi-Timiskaming Area by the Ontario Department of Mines). Figure 2 shows the results compared with the previous investigations of this area by the alpha counting method [SLACK, 1949]. The overall agreement between the two methods seems quite satisfactory and the new results do not significantly alter the previous geological interpretation for this area. It was noted in particular that, as expected, the scatter in results was somewhat reduced. There also seems to be an increase in the radioactivity of the country rock from south to north. The number of determinations was, however, not sufficient to make this point absolutely certain.

Discussion of results for Elzevir Batholith--Figure 3 shows the results obtained on and around the Elzevir Batholith situated in southeastern Ontario, 40 mi north of Belleville and 12 mi east of Madoc (see Map 51d of the Grimsthorpe Kennebec Area by the Ontario Department of Mines). This area had previously been investigated [INGHAM, 1943]. The results obtained from the one complete profile show a significant decrease in radioactivity towards the center from both the eastern and western edges. The general absence of roads towards the center of the batholith limited the scope of the investigation. From the results obtained it would appear impossible to distinguish clearly between different rock types by means of their average radioactivity as shown in Table 1.

Table 1--Radioactivity of rock types

Type of rock	Number of determinations	Average radioactivity equivalent ∝/mg/hr
Grey granite	50	1.0 ± 0.2
White granite	8	0.7 ± 0.2
Aplitic granite	2	0.80 ± 0.10
Quartz diorite	7	1.2 ± 0.3

Previous determinations gave for grey granite a mean of 1.1 ± 0.4 ∝/mg/hr for 89 specimens [INGHAM, 1943]. It is interesting to note the relatively high value for the belt of sediment (1.1 ± 0.2 ∝/mg/hr) along the southeastern rim of the batholith compared with the country rock. This again suggests the possibility that the more highly radioactive surface rocks of the batholith have been eroded to form this belt of sediments [SLACK, 1949].

Direct comparison with alpha counting method--Measurements were taken at stations along a large road cut 14 mi north of Orillia on Highway 11. Both glaciated and fresh surfaces of Pre-Cambrian granites, gneisses, pegmatites and biotite schists were exposed. At each station samples were taken for alpha determinations in the laboratory. Table 2 shows the comparison.

All field readings were taken at points within 100 yd of each other and show the large variations to be expected over very limited exposures of Pre-Cambrian rock. The results obtained by the

Table 2--Radioactivity of rocks north of Orillia

Rock number	Type of rock	Count/5 min corrected for background	Radioactivity	
			Field value	Laboratory value
			α/mg/hr	α/mg/hr
1	Pegmatite gneiss	4170	1.8	2.21
2	Granite gneiss	3870	1.7	1.14
3	Granite gneiss	3840	1.7	5.93
4	Pegmatite	2630	1.2	1.33
5	Pegmatite	7480	3.3	4.31
6	Granite gneiss	1770	0.78	2.42
7	Granite gneiss	1940	0.85	1.72
8	Biotite schist	630	0.28	1.02
9	Biotite schist	890	0.39	0.89
10	Biotite schist	630	0.28	0.64
11	Biotite schist	1080	0.47	0.78
12	Biotite gneiss	3590	1.6	1.65
13	Pegmatite	6450	2.8	4.25

field method, for any particular rock type seem more consistent than those obtained by the laboratory method. However, the field values are somewhat lower than the laboratory results. This may be explained in terms of sampling uncertainties or in terms of the assumption made regarding the potassium content of rocks. It is hoped, in the near future, that the results of chemical analyses of some of these samples will become available and help to clarify this matter.

Furthermore, the field work indicated that effects due to weathering of rocks are slight and that it seems impossible, using lead absorption sheets, to analyze the separate radioactive contents of rocks. This was only to be expected. The results obtained were readily reproducable within the limits of statistical accuracy.

Conclusions--The operation of an anticoincidence field gamma counter on two batholiths has been discussed. The results have been presented and compared with those obtained by a laboratory alpha counting method.

It is felt that when the effect of potassium has been further studied the speed at which results can be obtained gives the method a decided advantage over previous methods. In the summer of 1950 it is hoped to have a portable three-channel system in operation. This will not only increase the sensitivity further but will also facilitate the collection of data in previously inaccessible areas.

Acknowledgments--We are indebted to J. Tuzo Wilson and E. C. Bullard for suggesting this problem and for their assistance, and to the National Research Council for financing the summer's field operations. The alpha activities were determined in the laboratory as part of a project supported by Research Council of Ontario.

References

BROWN, SANFORD C., Theory and operation of Geiger-Mueller counters, II, Nucleonics, v. 3, pp. 50-64, 1948.

BULLARD, E. C., Radioactive heat generation in rocks, Geophys. Supp. Mon. Not. R. Astron. Soc., v. 5, no. 2, 1942.

HESS, V. F., Further experiments on the surplus γ radiation from granite, Phys. Rev., v. 72, p. 609, 1947.

INGHAM, W. H., Structure and radioactivity of the Bourlamaque and Elzevir Batholiths, Univ. Toronto, 1943 (unpublished thesis).

KEEVIL, N. B., Radiogenic heat in rocks, J. Geol., v. 51, 1943.

KEEVIL, N. B., Thorium-uranium ratios in rocks and minerals, Amer. J. Sci., v. 242, p. 309, June 1944.

KEEVIL, N. B., and Others, Causes of variations in radioactivity data, Amer. J. Sci., v. 241, pp. 345-365, 1943.

SAWYER, G. A., and M. L. WIEDENBECK, Gamma-ray of K_{40}, Phys. Rev., v. 76, no. 10, 1949.

SLACK, H. A., Radioactivity measurements in the Kirkland Lake area, Trans. Amer. Geophys. Union, v. 30, p. 867, 1949.

Geophysics Laboratory,
University of Toronto,
Toronto, Ontario, Canada

(Communicated manuscript received June 19, 1950, and, as revised, October 25, 1950; open for formal discussion until July 1, 1951.)

Transactions, American Geophysical Union Volume 32, Number 1 February 1951

A COMPARISON OF SEVERAL HEAT AND MASS TRANSFER NETWORKS OF INTEREST IN WATER CONSERVATION

Heinz F. Poppendiek and Myron Tribus

Abstract--Electrical networks descriptive of the heat and mass transfer processes occurring in the systems such as lakes, open fields, snow banks, and United States Weather Bureau evaporation pans, are presented and discussed. Suggestions for research and correlation of measurements are given on the basis of an examination and comparison of the networks.

Introduction--Exact solutions to most heat and mass transfer problems can only be obtained by the solution to the diffusion equation. There has been a growing appreciation, however, for the fact that many "field" problems may be solved with a satisfactory approximation by "network" methods, that is, treating in place of a system of spatially distributed quantities an approximately similar system comprised of "lumped" parameters. This method of analysis often results in a better overall view of the problem. It is the purpose of this paper to show how this network approach may be applied to the following systems involving large scale heat and mass transfer (evaporation): (a) an open field, (b) a melting snowbank, (c) a lake, and (d) an evaporation pan.

The treatment of problems in heat transfer [TRIBUS and MORRIN, 1948], mechanics [MILES, 1943], and electromagnetic radiation [McALLISTER, 1944], by the consideration of an equivalent network has permitted profitable analysis by analogic means, and what is equally important, has provided a terse graphic means of portraying the important variables in a complicated system. The thermal or mass flow network has the same significance in diffusion problems as has the free body diagram in mechanics. The important variables stand out unencumbered by non-essential details.

A brief search of the literature revealed that this mode of analysis has not been brought to bear upon the problems of large scale evaporation in such systems as open earth fields, lakes, or snowbanks. Many workers are active in this field, each, in general, attacking one portion of the network. If the presentation of the complete systems (via network representation) serves to show the common features in these many investigations, the purposes of this paper will have been met.

Symbols and subscripts--The following symbols are used:

A = area, sq ft
B = barometric pressure, inches Hg
f_c = unit thermal conductance, Btu/hr ft^2 °F
f_m = unit mass conductance, lb/ft^2 hr (lb/lb)
g = mass flux, lb/hr
H = specific humidity, lb water/lb air
k = thermal conductivity, BTU/hr sq ft (°F/ft)
L = latent heat of vaporization for water, BTU/lb
P = vapor pressure of water, in Hg
q = heat flux, BTU/hr
R = thermal resistance, °F/BTU/hr
t = temperature, °F
τ = temperature of receiver, °F
y = distance from surface, ft
$\triangleq$ means equal by definition

The following subscripts are used:

c = convection of heat
m = mass transfer
s = surface
∞ = "free stream"
dp = dew point
mr = mean radiant
f = mixed mean fluid

The network parameters--A simple example of the network technique may be found in the case of convective heat transfer to or from a fluid flowing in a pipe. (The heat conduction equation for a moving fluid is in many cases the same for the atmosphere as for the fluid in the pipe; only the boundary conditions and scale of turbulence are changed.) The thorough way of studying the details of the heat transfer mechanism is certainly to solve the fluid flow (hydrodynamic) and temperature (thermal) equations simultaneously. Even for such a simple system as flow in a pipe the problem is not easy, in fact, only for a few systems have the equations been solved. On the other hand, the compelling reason for solving these equations is the desire to predict the behavior of heat exchange equipment involving flow in tubes. Since this requires only the magnitude of the heat flow across the boundary, it is customary to define a "unit thermal conductance" (known also as a "heat transfer coefficient" and "film coefficient"; called "conductance" here to emphasize its role in the circuit) according to

$$q \triangleq f_c A(t_w - t_f) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where A is the area through which heat flows, and subscript w relates to the pipe wall.

The product $f_c A$ corresponds to the "conductance" of an electrical circuit; the reciprocal is referred to as a "thermal resistance" and is indicated in thermal circuits by the same symbol as is used for a resistor in electrical circuits.

How has the introduction of this symbol simplified the problem? Also, how does it relate to the solution we would obtain were we to solve the classical equations for the heat transfer in the fluid? The last question may be answered first. If the solution to the fluid flow and heat transfer equations were available we would have on hand some function which described the temperature distribution in the flowing fluid. This function would then be differentiated and the heat flow determined from the gradient of temperature at the wall of the tube, that is from

$$q \triangleq -kA(dt/dy)_{y=0} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

From the definition of the conductance it is evident that the unit thermal conductance is related to the gradient of temperature in the fluid by the equation

$$f_c = -[k(dt/dy)_{y=0}]/(t_w - t_f) = -k\left\{\partial[(t - t_f)/(t_w - t_f)]/\partial y\right\}_{y=0}$$

The use of the unit thermal conductance for heat transfer then is a way of discussing the behavior of the all important gradient of dimensionless temperature at the boundary in the absence of information about the entire temperature field. This gradient (or the conductance) is a function of many parameters, which affect the hydrodynamic and thermal equation, the fluid properties, nature of boundary layer, flow velocity, and stability, all of which concern us. Lack of exact knowledge of the entire field does not prevent us from considering the conductance and also does not prevent us from measuring it.

If, in a thermal system, the temperature is a function of time, one must consider the effect of thermal capacity. It is evident that the analogous electrical quantity is the capacitance. In thermal circuits the accepted symbol for a capacitor is used. In an analogous fashion the defining equation for the unit conductance for mass transfer is given by

$$g \triangleq A f_m (H_S - H_\infty) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

The definition for the conductance is seen to consider that the driving potential for mass transfer is the concentration (or specific humidity). Obviously other potentials could be chosen; the conductance would then take on a different numerical value and different units. The proper potential to take is probably the fugacity of the water, but the vapor pressure is easier to measure. If the vapor pressure is taken as the potential, but the conductance is retained in the manner defined above, the resulting equation for the mass transfer is

$$g = A f_m\, 0.62\, (P_S - P_\infty)/B \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Associated with each pound of water evaporated, there is L, the heat of vaporization, approximately 1050 BTU/lb. The energy transfer associated with the evaporation process is therefore given by

$$q_e = A f_m\, 0.62\, L\, (P_S - P_\infty)/B \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

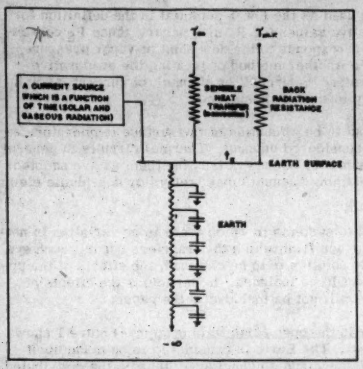

A CURRENT SOURCE WHICH IS A FUNCTION OF TIME (SOLAR AND GASEOUS RADIATION)
REVERSIBLE HEAT TRANSFER (CONVECTION)
BACK RADIATION RESISTANCE
EARTH SURFACE
EARTH

Fig. 1--Thermal network for Earth system (in the absence of mass transfer)

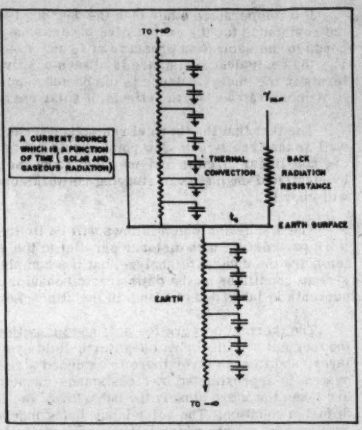

A CURRENT SOURCE WHICH IS A FUNCTION OF TIME (SOLAR AND GASEOUS RADIATION)
THERMAL CONVECTION
BACK RADIATION RESISTANCE
EARTH SURFACE
EARTH

Fig. 2--Thermal network for Earth system with convective path in its more complete form (in the absence of mass transfer)

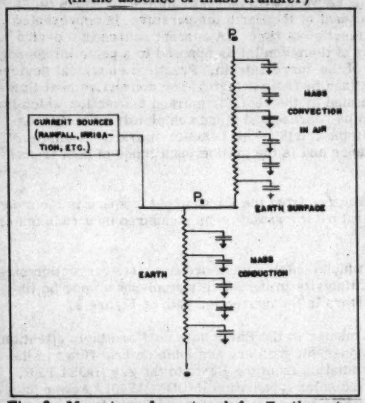


Fig. 3--Mass transfer network for Earth system

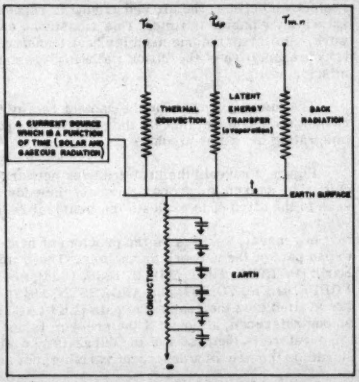


Fig. 4--Energy transfer network for Earth system with combined heat and mass transfer

The usual way of defining the thermal resistance is by means of the equation

$$q = \Delta t/R \quad \ldots\ldots\ldots\ldots\ldots (6)$$

The temperature difference to be used is somewhat arbitrary in most convection systems, the choice of temperature difference determining the magnitude of the resistance. For the mass transfer resistance one potential is taken as the temperature of the surface in question, the other, for reasons which will become apparent later is taken as the dew point of the air at the position where P_{∞} is measured.

The thermal resistance is therefore given by the following equation, obtained by eliminating q from the previous two equations

$$R_e = [(t_g - \tau_{dp})/(P_g - P_{\infty})](1.61/L)(B/t_m A) \quad \ldots\ldots\ldots\ldots\ldots (7)$$

If a temperature other than the dew point is used as the lower potential in the definition for the resistance for the evaporative process, negative values for R_e may occur. Since P_S corresponds to the saturation pressure at t_S and τ_{dp} corresponds to the dew point at vapor pressure P_∞, the equivalent resistance is always positive. Another method of treating the evaporative terms in the energy balance is to consider equivalent "sources" or "sinks" of current, as will be demonstrated when the effects of solar energy input are considered.

The fact that the thermal resistance turns out to be a function of the surface temperature as well as the free stream dew point should not be considered unusual. Thermal circuits in general are non-linear circuits and one must adopt the same techniques in treating them as are adopted by electrical engineers in studying networks containing vacuum tubes, relays or non-ohmic elements with thyrite.

The discussion which follows will be limited to systems in which there is no variation in network parameters with distance parallel to the surface from which the transfers occur. Such systems are the easiest to analyze, but if a complete solution is to be obtained, the effects of the upstream conditions on the downstream behavior should be included. In particular the effects of currents in lakes and of fronts in the atmosphere will not be included in the paper.

The thermal network for heat and mass flow in the open earth field system--Figure 1 shows the thermal circuit for an open Earth-field system. The Earth is considered to be made up of layers and to each layer there is assigned a resistance and a capacitance (that is, the distributed system is approximated by a resistance-capacitance (RC) network). The more finely the divisions are taken the more closely the behavior of the RC network will approximate the solutions to the diffusion equation. The solar input, being independent of the Earth temperature, is represented by a current source which follows a prescribed function of time. (A current source is a device which supplies a current to a network regardless of the potential as opposed to a potential source which maintains a constant potential regardless of the current drain. Practical electrical devices for this purpose function only in a limited range fixed by their design.) The convective heat flow resistance between the air and ground is represented by the resistor marked convection which is extremely variable in time. This resistance can be represented more completely by an RC network, similar to the one used for heat transfer in the Earth. The resistor marked "radiation" is representative of the "back radiation" resistance and is the predominant mode of heat transmission at night.

The lower potential for the radiant energy transfer from the Earth to outer space is the mean radiant temperature, that is, the effective temperature for radiation as measured by a radiometer integrating over a hemisphere.

Figure 2 reveals the heat-transfer network which contains the more complete convection circuit. The search for proper values of the eddy diffusivity in the Earth's atmosphere may be likened to the attempt to evaluate the indiviual resistors in the convection path of Figure 2.

In general, workers on the problem of heat transfer in the Earth have confined their attention to one part of the network or another. Thus, considerable data are available on heat flows in the Earth [PATTEN, 1909; SMITH, 1938, 1939], net radiation from the Earth to the sky [BOELTER, POPPENDIEK, YOUNG, and ANDERSEN, 1949], and solar irradiation [MOON, 1940]. Fewer data are available on the convective path [LETTAU, 1939]. Most workers use the Earth temperature as one reference, although if the problem is one of predicting heat flow it is seen that the surface temperature is the result of the currents in each part of the network and surface temperature should be treated as a dependent variable, not as the independent one.

In parallel with the thermal network there exists a mass-flow network. Figure 3 shows the network representation for the mass transfer. Moisture is exchanged between the Earth and air. The soil represents a resistance to the transfer of moisture which has been studied [SMITH, 1943] but seldom treated in conjunction with the resistance to convective transfer in the air.

Actually the heat- and mass-transfer networks are in action at the same time. The two modes of energy transfer affect one another in several ways. The moisture content of the soil influences the thermal conductivity and heat capacity of the Earth. The temperature at the Earth's surface influences the vapor pressure there. The moisture content of the air in turn affects the resistance to radiation and the magnitude of the nocturnal radiation.

Figure 4 shows the network which represents the combined transfers of energy to or from the Earth's surface. It would serve no useful purpose to add to the diagram the indications of how the

one resistance is affected by the current flows in other branches, but these mutual effects must be considered when "analyzing" the network.

The network for a snowbank system--Because the largest evaporation rate for snowbanks probably occurs when the snow is in the process of melting, this case will be considered. The case of the snowbank when the snow is not melting is simpler and can easily be treated when the more complicated case is understood.

Figure 5 shows the network drawn to represent the energy-transfer processes in the snowbank. As shown in Figure 5, the surface of the snowbank stays at 32° F while the snow is melting. A battery is indicated as maintaining the surface "potential" (temperature) constant in much the same fashion as the latent heat of fusion serves to hold the temperature fixed. (The current flow to or from the battery simulates the amount of heat transferred during melting or freezing.) The input energy from the Sun, indicated by the current source, is not all absorbed at the surface of the snowbank, but is rather absorbed in successive layers. The snowbank has a very low thermal conductivity and diffusivity. The heat transmission within the snowbank is represented by the RC network. The snowbank rests upon the Earth and the conduction of heat in the Earth is represented by the RC network shown. Radiation to the sky and convection to the air are shown as before.

The network for a lake--Figure 6 shows a network which has been drawn to illustrate energy flow paths for a lake system. In Figure 6, the various resistances which occur in the network within the lake are all functions of the turbulence occuring in the water. Thus the wind, the viscosity, the temperature distribution, and lake currents affect the magnitudes of the resistances. Like the case of the snowbank, the water does not absorb the solar energy at the surface of the lake, but rather there is a steady absorption from the top down. The absorptivity of the water depends upon its purity. Data on the absorptivity of pure water are given in MOON [1936] and HULBURT [1926]. These data indicate that at a level of one foot beneath the surface of the lake, 60 per cent of the energy has been absorbed. (The usual exponential law may be applied.)

The transfers of energy from the lake surface to the sky and air are accomplished by the same processes as exist in the Earth and snowbank systems. There will be a large difference between the evaporation rates from deep lakes as compared to shallow lakes. In a shallow lake (something just short of a marsh, say) a large fraction of the radiant energy will be absorbed at the bottom of the lake and considerable heat will be transferred by convection from the lake bottom to the water. This will lead to an instability and promote the convective transfer within the lake. Also, the capacity of the shallow lake will be less and the temperature of the surface will in general rise higher during the 24-hr cycle. Note that in a deep lake the solar radiation is absorbed in lesser and lesser quantities as one proceeds from the surface. This gives rise to a more stable daytime temperature distribution in the lake and does not promote convection.

The network for a pan--Because the evaporation pans are often used as a guide in the prediction of evaporation rates for lakes and other surfaces it is of interest to draw the equivalent network for the energy transfer processes occurring in a pan. Figure 7 shows a sketch of a standard Weather Bureau evaporation pan as installed in a typical location [U. S. WEATHER BUREAU, 1948]. Figure 8 indicates the equivalent network.

The relation between the resistances for convection and evaporation--WALKER, LEWIS, McADAMS, and GILLILAND [1937] and BOELTER, CHERRY, JOHNSON and MARTINELLI [1946] demonstrate that the conductances for heat and mass transfer should be proportional to one another. The latter reference shows that at temperatures near 50° F the ratio of f_c to f_m (conductance for heat transfer by convection to the conductance for mass transfer) is approximately 0.22 for an air-water system for either free or forced convection. These relations have been established for small scale convection systems, that is, wet bulbs, cooling towers, airplane wings in icing conditions, small spheres, flat plates, and other similar systems. There are good reasons to expect the relations to continue in large scale phenomena, but proof is at present lacking.

The two resistances will be proportional to one another provided, of course, the flow paths between them are the same. For this reason, the point at which the lower potential is selected must be the same for both heat and mass transfer. If the "air reference temperature" is taken at a five-foot level, then the "air dew point" should be taken at the same height. Eq. (8) gives the resistance for heat transfer

$$R_c = 1/f_c \ A \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

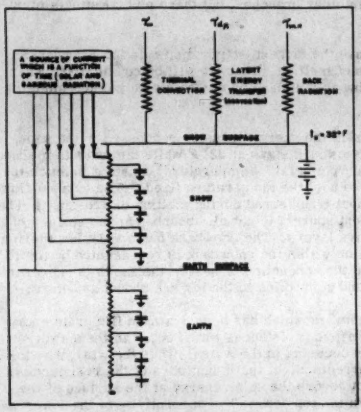


Fig. 5--Energy transfer network for a melting snowbank

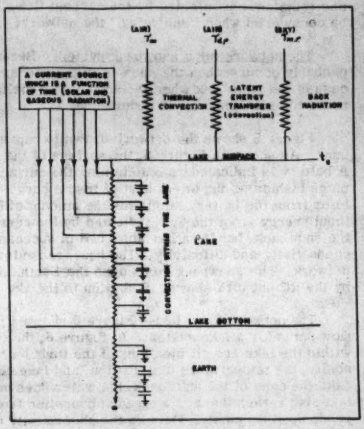


Fig. 6--Energy transfer network for a lake system

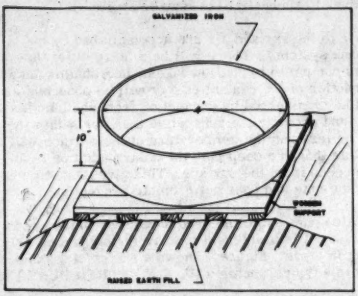


Fig. 7--Typical pan installation

Comparison with (7) indicates that the ratio of the two resistances, sensible to latent energy transfer, is given by

$$R_c/R_e = (t_m/t_c)[(P_s - P_\infty)/(t_s - \tau_{dp})]0.62\ L/B \quad \ldots\ldots (9)$$

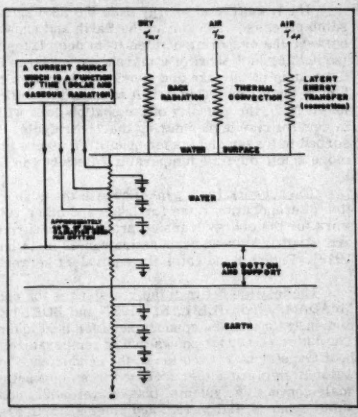


Fig. 8--Energy transfer network for pan system

Because of the previously mentioned ratio between the heat and mass-transfer conductances for a water-air system, the ratio between resistances noted in (9) is ultimately given by

$$R_c/R_e = 2.8(L/B)[(P_s - P_\infty)/(t_s - \tau_{dp})] \quad \ldots\ldots (10)$$

In the case of evaporation from a lake surface or from a melting snowbank the above ratio is a function of three parameters, the surface temperature, the free-stream dew point and the barometric pressure. The variation with barometric pressure is linear, hence a graph of this ratio as a function of two parameters will suffice. Figure 9 shows a graph of the ratio of the two resistances plotted against surface temperature with free stream dew point as a parameter for the

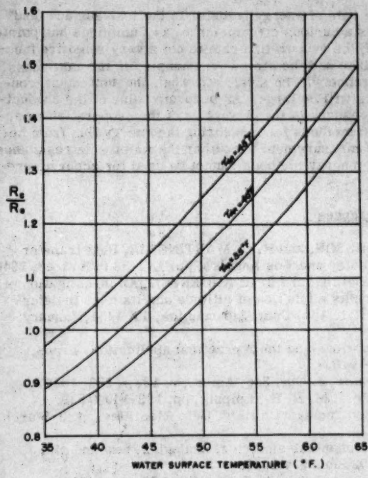


Fig. 9--Ratio of convective to evaporative resistances versus surface temperature for various free air dew points

lake and melting snowbank systems.

Some comments on the prediction of evaporation rates from lakes based upon consideration of the network characteristics--If wet- and dry-bulb air temperature, mean radiant temperature, back radiation resistance, latent heat resistance, sensible heat resistance, total hemispherical radiation, and water eddy diffusivity variations were known for the lake system, it would be possible to obtain a temperature solution by numerical or analog methods. If such a temperature solution were available, it would then be possible to calculate evaporation rates from the lake because the mass transfer potential would be known.

The most satisfactory and direct means of predicting the rate of evaporation from a surface is to know the magntiudes of the conductance, the surface vapor pressure and the vapor pressure in the free stream (wherever the "free stream" may be). This technique must be applied with care for the results are very sensitive to the accuracy of the measurements. For example, it is very difficult to determine the temperature of the surface of a lake. True, the water temperature may be measured, but it is the temperature at the interface which must be measured--a measurement taken two centimeters beneath the surface will be worthless, particularly at high evaporation rates where there will be steep gradients in the fluid. The vapor pressure of water changes very rapidly with temperature, and an error of five degrees F in temperature measurement may well mean an error of 65 per cent or more in predicted evaporation rate. The lake surface temperature may be measured by (1) making water temperature soundings in the uppermost water layers of the lake, or (2) dragging a light balsawood float, with an attached thermocouple under it, over the lake surface.

The determination of heat transfer convective conductances for the range of stability conditions encountered could be accomplished by measuring convective heat transfer rates and air temperature profiles over land. Such studies are at present being conducted by the Department of Engineering at the University of California.

Mass transfer convective conductances could be measured for a range of stability conditions over a smooth snowfield where ablation, radiation, and humidity measurements can be made; the classical work of SVERDRUP [1936] typifies the investigation that can be made.

Another technique for predicting evaporation is to set up an evaporation pan and multiply the ratio of areas of lake and pan by the pan evaporation rate and some empirically determined "coefficient." Until careful measurements have been made of the evaporation rates from a few lakes, such comparisons must necessarily be considered no more than enlightened guesses. A comparison of the networks for the pan and lake system indicated that few of the resistances are similar, the capacitances are unequal and the circuits are very different. Pan evaporation rates reveal little that could not be predicted from separate measurements of wind velocity, gustiness, humidity, solar irradiation and air temperature.

Energy methods, as consistently suggested by CUMMINGS [1940] are not satisfactory for lake systems, for these energy methods usually suggest that the energy is absorbed at the lake surface. It has been shown, however, that the absorption of the radiation occurs gradually with depth and that the surface temperature of the lake depends upon the magnitude of the convective resistances within the lake as well as the external ones. If the resistance to heat transfer within the lake were known, the energy method would have considerable value particularly when modified to take into account the actual processes occurring. Suppose that the conductance within the lake were known and the temperature beneath the surface were also known at a particular depth. If the surface temperature of the lake were known (but not necessarily with the precision required for

accurate knowledge of the vapor pressure), the rate of energy transfer to the lake surface (and thence to the air) might be computed. Now it is a curious circumstance, as Cummings has pointed out, that if the heat flow from the lake is given, the evaporation rate is not a very sensitive function of the unit mass conductance between the lake and the air. For example, if the unit mass conductance is large, the vapor pressure difference will be small and when the unit mass conductance is small the vapor pressure difference will be large. An accurate value of the conductances between the lake and air would not be necessary to the prediction of the evaporation rate. Unfortunately, there are available at present no methods for measuring the energy flux from beneath the surface of the lake. Until methods of measurement for either the water side resistance or the water side energy flux are available, the energy methods cannot be used for accurate prediction of evaporation rates from lakes.

References

BOELTER, L. M. K., V. H. CHERRY, H. A. JOHNSON, and R. C. MARTINELLI, Heat transfer notes, University of California Press, Berkeley and Los Angeles, pp. LVI-38 to XVI-43, 1946.

BOELTER, L. M. K., H. F. POPPENDIEK, G. YOUNG, and J. R. ANDERSEN, An investigation of aircraft heaters--XXX Nocturnal irradiation as a function of altitude and its uses in determination of heat requirements of aircraft, Nat. Adv. Com. Aeronautics, TN 1454, January, 1949.

CUMMINGS, N. W., The evaporation-energy equations and their practical application, Trans. Amer. Geophys. Union, pt. 2, pp. 512-522, 1940.

HULBURT, E. O., The transparancy of ocean water, J. Opt. Soc. Amer., v. 13, p. 553, 1926.

LETTAU, H., Atmosphärische Turbulenz, Ak. Verl. M. B. H., Leipzig, pp. 133-149, 1939.

McALLISTER, J. F., Equivalent circuit of an electromagnetic field, Gen. Elec. Rev., p. 9, March, 1944.

MILES, J. W., Applications and limitations of mechanical-electrical analogies, new and old, J. Acoust. Soc. Amer., v. 14, no. 3, pp. 183-192, January 1943.

MOON, P., The scientific basis of illuminating engineering, McGraw-Hill, 168 pp., 1936.

MOON, P., Proposed standard solar radiation curves for engineering use, J. Franklin Inst., v. 230, pp. 583-617, 1940.

PATTEN, H. W., Heat transference in soils, U. S. Dept. Agric. Bur., Soils Bull. 59, 1909.

SMITH, W. O., and H. G. BYERS, The thermal conductivity of dry soils of certain of the great soil groups, Soil Sci. Soc. Amer., Proc., v. 3, pp. 13-19, 1938.

SMITH, W. O., Thermal conductivities in moist soils, Soil Sci. Soc. Amer., Proc., v. 4, pp. 32-40, 1939.

SVERDRUP, H. U., The eddy conductivity of the air over a smooth snow field, Geofys. Pub., Norske Vidensk.-Akad. Oslo, v. 11, no. 7, 1936.

U. S. WEATHER BUREAU, Instructions for the installation and operation of weather bureau Class A evaporation stations, (Instructions issued in conjunction with Weather Bureau Circular L), Washington D. C., August 1948.

WALKER, W. H., W. K. LEWIS, W. H. McADAMS, and E. R. GILLILAND, Principles of chemical engineering, McGraw-Hill, 591 pp., 1937.

TRIBUS, M., and E. H. MORRIN, Elementary heat transfer, University of California Press, Berkeley and Los Angeles, 130 pp., 1948.

Department of Engineering,
University of California,
Los Angeles 24, California

(Manuscript received March 20, 1950; presented at the Twenty-Fifth Regional Meeting, Davis, California, February 3, 1950; open for formal discussion until July 1, 1951.)

Transactions, American Geophysical Union Volume 32, Number 1 February 1951

SURFACE DETENTION, RATE OF RUNOFF, LAND USE, AND EROSION RELATIONSHIPS ON SMALL WATERSHEDS

Leonard Schiff

Abstract--Infiltration curves were derived for small watersheds in various land use without using relationships of rate of surface runoff, q, and surface detention, D. Relationships between q and D were then determined for both the rising and falling sides of hydrographs and were represented by equations having the form $q = KD^m$. Appreciable differences in m were found between the rising and falling sides of each hydrograph. These differences are contrary to former findings which were based largely on plot data.

Theoretically and experimentally, others have shown that m is 3.0 for laminar flow. Experimental evidence indicates that m is approximately 1.67 for turbulent flow. Values of m, particularly for the rising side of hydrographs, were found to increase as the height and density of crop increased. Most of the flow for such values is in the laminar range. However, such values represent averages over the watershed area and certain portions of the flow occur in rivulets where velocities and depths are greater than the average. This results in a Reynolds number in the range of turbulent flow. Values of m on the falling side of the hydrograph were always in the turbulent range, except for a few values in the transition range between laminar and turbulent flow.

Average-flow velocities of surface water detention were determined based on the rates of runoff, depth of surface detention, and the area and shape of watersheds. Relationships between velocities so determined and those actually measured on plots are indicated. Velocities increased with slope and were highest under corn coincident with the greatest erosion. For reasonably similar velocities in wheat and corn areas, erosion was less under the former indicating the greater binding power of more numerous roots. Erosion was also rather low under meadow. Average flow velocities in contour corn-land were noticeably less than those in straight-row cornland. Such cover generally plays in important part in reducing the impact of raindrops, in binding and holding soil, and in reducing the velocity of surface detention.

Introduction--Knowledge of relationships between rates of runoff and the depth of surface detention or overland flow is important in analyzing and synthesizing the hydrograph. Land use and the physiography affect these relationships. For a given rate of flow and a given topography the land use has an appreciable effect on the depth of surface detention or overland flow. The depth of surface detention will increase to the extent to which the land use subdivides the flow and offers resistance to flow. An increase in surface detention for a given rate of flow and topography will result in a decrease in the velocity of flow. Velocity of flow is an important factor in removing soil from any vicinity. Since erosive force is a power of the velocity, land use which reduces this velocity is important.

Relationships between velocities of flow as surface detention determined from plot studies and watershed studies are indicated and are of value in the interpretation of field performance. The velocity and type of flow, whether laminar or turbulent, and resultant erosion under different land use represent important considerations in the utilization of land. Such information is included herein.

Experimental procedure--Rainfall, runoff, and soil loss data for major storms during the period 1940-1949 were obtained from six crop watersheds, three in poor and three in good land-use practices. These watersheds range in size between 0.65 and 1.69 ac and follow a four-year crop rotation of corn, wheat, meadow, and meadow. Rainfall and runoff data were obtained from three grass watersheds, one poor and two of good land use practices. These watersheds range in size between 1.63 and 2.71 ac and are in pasture or permanent meadow. Studies of overland flow on small forested watersheds were not included because of the shallow depth of flow.

Terms and symbols used are listed below.

Infiltration = the passage of water through the surface of the soil into the soil mass
Surface detention = water in transit over the soil surface
D_a = average depth of surface detention

v_a = average velocity of flow of the water in surface detention
q = rate of surface runoff
m = slope of q and D_a logarithmic relationship
$K = \ln q = KD^m$, K represents intercept of line on q scale
Density of cover = per cent of the soil surface covered by plant canopies. (Weeds and other forms of vegetation are included.)
L = length of watershed
W = width of watershed

In order to determine relationships between rates of surface runoff and surface detention, infiltration curves for the small watersheds were derived independent of such relationships [SCHIFF, 1950]. As a by-product of the derivation of infiltration curves, surface detention values were obtained. Such surface detention values were plotted against measured rates of surface runoff for both the rising and falling sides of hydrographs. Lag time was accounted for. Relationships were established from single-peak sections of well-defined hydrographs. Whenever possible single-peak hydrographs were used. Portions of multiple-peak hydrographs were not combined.

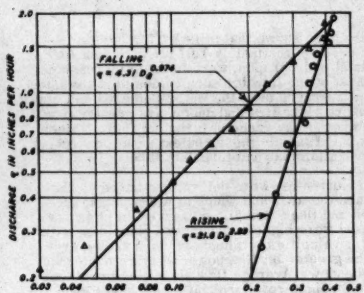


Fig. 1--Storm of June 16, 1946, Watershed 123, relationship of surface detention to discharge

Figure 1 illustrates relationships found between q and D for the storm of June 16, 1946 on Watershed 123, represented by the equation having the form $q = KD^m$ [HORTON, 1935], thus: for the rising side of the hydrograph $q = 21.6\ D_a^{2.89}$; for the falling side of the hydrograph $q = 4.31\ D_a^{0.974}$.

The value of m for the rising side of the hydrograph is 2.89. Theoretically and experimentally, others have shown that m is 3 for laminar flow. The value 2.89 indicates that flow on the rising side is largely laminar. The value of m for the falling side is 0.974. Experimental evidence indicates that m is approximately 1.67 for turbulent flow. The value 0.974 indicates that flow on the falling side is turbulent. It is not the intention of this paper to discuss the absolute meaning of different values of m but rather to present the values of m found under different conditions. To a certain extent an attempt is made to interpret major influences on the values found. It must be borne in mind that m represents average values over the watershed area and certain portions of the flow occur in rivulets where velocities and depths are greater than the average. For such flows of greater velocity and depth Reynolds number is higher, in the range of turbulent flow. Also, as has been pointed out at times, among other factors affecting the value of m are differences in depths of surface detention on the upper and lower parts of a watershed and rainfall impact.

The velocity of the water in surface detention was measured directly on plots using floats and a dye and the average velocity of surface flow on small watersheds was computed. It seemed necessary to use a method which would lead to a common basis of comparison for the various watersheds. The ratio of the maximum length of the watershed to its maximum width at right angles to this length was determined. For example, the maximum length of Watershed 123 is 370 ft and the maximum width is 330 ft. The length divided by the width is 1.12, or L = 1.12W. The maximum length expressed as a ratio of the width multiplied by the width as unity was considered equal to the area of the watershed in square feet, that is, $1.12W \times W = 1.37\ (ac) \times 43560$, or W = 231 ft. The width when multiplied by the average depth of surface detention and the velocity is equivalent to the rate of surface runoff. For example, for the storm of June 16, 1946 on Watershed 123 the maximum D_a was 0.43 inch and the maximum q was 2.64 cu ft/sec. Then $231 \times (0.43/12) \times v_a = 2.64$, and v_a is equal to 0.32 ft/sec.

Various relationships involving surface detention, rate of runoff, velocity, land use, type of flow, and erosion were tabulated and plotted for some of the large storms on the nine watersheds described above. Interpretation of various phenomena is made.

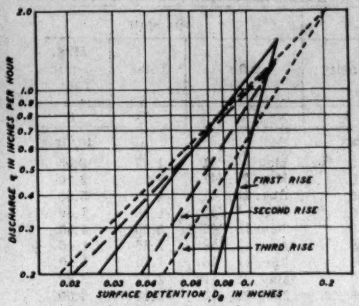


Fig. 2--Storm of May 22, 1941, Watershed 109, reduction in m for successive rises

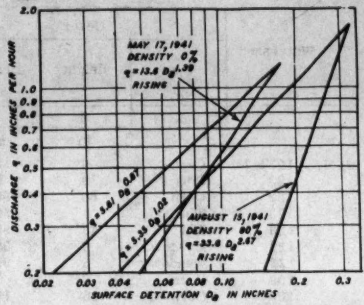


Fig. 3--Values of m for various densities of corn, Watershed 123

D_s and q relationships--Table 1 presents values representing the relationships found between D_s and q. Columns 12 and 14 show a higher value of m for the rising side as compared to the falling side of the hydrograph. That is, the slope of this relationship for the rising side of the hydrograph is steeper. In other words, for identical runoff rates, the average depth of detention storage on the watershed on the rising side of the hydrograph was found to be noticeably greater than that for the falling side. The magnitude of the difference is illustrated in Figure 1 and by the equations given. Since lag time was accounted for, reasons for such differences probably include: (1) a decrease in resistance to flow caused by the removal of some loose soil and residue; and (2) the formation of rivulets for flow which increases the hydraulic radius by reducing the wetted perimeter. This is illustrated by surface detention and discharge relationships for a multiple-peak hydrograph shown in Figure 2. Note that the slopes or m value of the first, second, and third rise decrease. That is, for a given rate of runoff the depth of surface detention decreases. Although the slopes of the first, second, and third fall also decrease, the decreases are not so great. Presumably the slope of the rise should approximately equal the slope of the fall when the surface of the watershed has become stable. The angle made between the first rise and first fall is about 22° whereas the angle between the third rise and third fall is about 13°. Apparently the successive peaks "lubricate" the watershed and improve factors affecting flow. Practically all previous work on hydrograph analyses and syntheses has used the assumption that both rising and falling sides of the hydrograph had the same detention-discharge relationship.

Density of cover and m relationships--There are indications that m increases as the density of a given cover increases. For example, Figure 3 shows that m increased from 1.39 to 2.67 for the rising side of the hydrograph as corn increased in density from zero to 80 per cent on Watershed 123. This seems reasonable and consistent with an increase in resistance to flow.

Considerable differences appear in m for improved and poor practice watersheds, particularly when the land use practices appreciably affect the land surface. Contour farming practiced on Watershed 121 resulted in higher values of m compared to the straight-row farming practiced on Watershed 106, as shown in Column 12, Table 1.

V_s and cover density--The average velocity of surface flow on watersheds was computed as mentioned previously. To indicate the accuracy of such computations some comparisons were made with direct measurements on plots. Velocities were measured with a dye on plots 6 × 60 ft on a ten per cent slope with water applied at such a rate that discharge was approximately 3.5 in/hr. After sufficient length of run, velocities on bare soil on plots became approximately constant at 0.7 ft/sec. For conditions on watersheds reasonably comparable to that on plots, data and velocities taken from Table 1 are summarized in Table 2.

At a discharge of 3.5 in/hr, velocities under corn stubble and weeds were found to be approximately 0.25 ft/sec on plots. This value is somewhat lower than found on watersheds where vegetation offered comparably high resistance to flow, as shown in Table 1. At a discharge of 3.5 in/hr the highest velocity found in the main small channel running the long direction of a plot on a ten per cent slope was 2.14 ft/sec. On Watershed 106, whose straight furrows are on a fairly steep

Table 1--Cover, rainfall, runoff, surface detention.

Watershed	Cover			Rainfall		
	Type	Height	Density	Date	Total	Max. 3-min. rate
	1	2	3	4	5	6
		in	pct		in	in/hr
123[a]	Corn	0	0	May 17, '41	1.47	2.00
123	Corn	0	0	May 22, '41	2.35	3.20
123	Corn	80	80	Aug. 15, '41	2.57	5.00
123	Wheat	6	30	May 6, '40	1.00	7.60
123	Wheat	40	88	June 16, '46	3.00	4.50
123	Meadow	5	95	Apr. 11, '48	1.55	1.40
123	Meadow	5	95	Apr. 13, '48	1.16	1.50
109[b]	Corn	0	0	May 22, '41	2.53	3.80
109	Corn	26	18	June 29, '41	2.41	6.00
109	Wheat	12	45	May 24, '40	1.68	1.60
109	Wheat	36	66	June 12, '40	0.64	2.80
109	Wheat	35	65	June 18, '40	1.54	4.40
109	Wheat	37	68	June 28, '40	1.89	5.00
109	Wheat	40	98	June 16, '46	2.77	4.50
103[c]	Corn	10	6	June 16, '46	3.03	5.80
103	Corn	90	68	July 21, '46	1.73	2.90
103	Wheat	24	58	May 31, '43	2.56	6.40
103	Wheat	38	65	June 28, '40	1.64	4.80
103	Meadow	6	80	July 7, '41	2.00	4.60
103	Meadow	5	72	Sep. 23, '45	3.00	3.80
110[d]	Corn	10	5	June 16, '46	3.03	5.80
110	Corn	27	10	June 20, '42	0.73	6.00
110	Corn	92	68	July 21, '46	1.73	2.90
110	Wheat	33	65	June 28, '40	1.64	4.80
110	Meadow	5	55	July 23, '40	1.12	3.80
110	Meadow	1	50	Feb. 26, '46	1.26	1.20
110	Meadow	6	85	July 7, '41	2.00	4.60
106[e]	Corn	14	23	June 24, '48	0.66	4.60
106	Corn	33	70	July 27, '48	1.22	4.80
106	Corn	84	95	Aug. 23, '44	1.33	8.20
106	Meadow	8	75	June 28, '40	1.47	4.00
106	Meadow	10	60	Sep. 23, '45	2.98	3.75
106	Meadow	12	100	June 16, '46	2.80	5.20
121[f]	Corn	35	75	July 27, '48	1.22	4.80
121	Corn	84	95	Aug. 23, '44	1.33	8.20
121	Meadow	3	60	June 16, '46	2.80	5.20
121	Meadow	14	99	Aug. 16, '47	2.40	4.00
129[g]	Pasture	8	90	June 28, '40	1.83	7.20
129	Pasture	4	95	Aug. 16, '47	1.85	3.60
135[h]	Pasture	14	94	June 16, '46	2.74	4.35
135	Pasture	8	85	June 28, '40	1.83	7.20
135	Pasture	5	55	July 7, '41	2.00	4.60
135	Pasture	8	75	July 23, '40	1.58	5.80
135	Pasture	5	80	Aug. 16, '47	1.85	3.60
135	Pasture	10	70	Sep. 23, '45	2.31	3.20
130[i]	Meadow	4	50	June 16, '46	2.39	5.10
130	Meadow	7	86	Sep. 23, '45	2.57	3.60

[a]Watershed 123: 1.37 acres, 5.8 per cent average slope, conservation practices used as defined below, Keene silt loam.

[b]Watershed 109: 1.69 acres, 12.7 per cent average slope, conservation practices used as defined below, Muskingum silt loam.

[c]Watershed 103: 0.65 acres, 11.3 per cent average slope, conservation practices used as defined below, Keene silt loam.

(continued)

type of flow, erosion for small watersheds

Runoff				$q = KD_a^m$				Flow type[j]		Erosion per acre
Total	Maximum			Rise		Fall		Rise	Fall	
	D_a	q	v_a	K	m	K	m			
7	8	9	10	11	12	13	14	15	16	17
in	in	in/hr	ft/sec							lb
0.42	0.16	1.27	0.57	13.6	1.39	5.61	0.87	T	T	1680
1.11	0.17	1.48	0.63	44.5	1.93	8.24	0.98	L T	T	7740
0.74	0.33	1.75	0.38	33.6	2.67	5.35	1.02	L T	T	860
0.24	0.09	1.00	0.82	20.0	1.24	7.60	0.84	T	T	1330
1.15	0.43	1.91	0.32	21.6	2.89	4.31	0.97	L T	T	39
0.31	0.18	0.25	0.32	13.7	2.66	9.78	0.80	L T	T	....
0.36	0.09	0.12	4073	4073.0	3.46	8.50	0.84	L	T	....
1.30	0.21	2.04	0.73	22.2	1.53	8.94	0.95	T	T	12250
0.94	0.26	3.14	0.89	48.6	2.04	15.3	1.19	L T	T	14270
0.40	0.06	0.56	0.65	19.2	1.28	6.46	0.88	T	T	530
0.25	0.10	0.92	0.72	20.4	1.32	5.64	0.77	T	T	220
0.60	0.18	2.41	1.00	90.0	2.11	25.6	1.38	L T	T	600
1.12	0.22	3.55	1.21	5192.0	4.78	22.4	1.21	L	T	1080
0.47	0.24	1.41	0.45	18.1	1.76	4.34	0.78	L T	T	45
1.47	0.30	3.45	0.65	19.8	1.46	11.74	1.03	T	T	540
0.20	0.08	0.73	0.53	36.3	1.53	6.86	0.888	T	T	240
0.73	0.17	1.26	0.42	1774.0	4.11	8.53	1.09	L	T	15
1.20	0.27	4.62	0.96	90.2	2.29	15.5	0.94	L T	T	1590
0.50	0.17	1.26	0.42	1143.0	4.12	5.84	1.15	L	T	90
0.99	0.26	1.54	0.33	296.0	3.95	5.32	0.94	L	T	....
1.75	0.27	3.73	0.99	65.4	2.18	28.0	1.54	L T	T	33990
0.25	0.16	2.82	1.24	299.0	2.54	30.6	1.31	L T	T	25200
0.35	0.09	1.25	0.98	57.0	1.59	6.74	0.70	T	T	1840
0.89	0.15	2.87	1.37	54.6	1.54	20.61	1.03	T	T	2500
0.45	0.16	2.47	1.06	122.4	2.16	20.24	1.17	L T	T	2410
0.17	0.06	0.09	0.11	28.8	1.96	1.92	1.08	L T	T	....
0.47	0.10	0.64	0.44	2667.0	3.64	18.48	1.47	L	T	100
0.32	0.09	1.82	1.65	52.3	1.40	14.96	0.88	T	T	9860
0.48	0.12	3.13	2.14	....	4.35	112.7	1.70	L	T	9480
0.94	0.35	7.63	1.80	115.8	2.54	27.6	1.20	L T	T	8040
0.01	0.12	2.61	1.72	243.7	2.49	13.76	0.92	L T	T	....
1.26	0.34	2.21	0.53	27.8	2.35	5.82	0.90	L T	T	....
0.49	0.27	1.54	0.47	17.2	1.84	5.20	0.94	L T	T	....
0.32	0.12	1.77	1.17	....	6.00	15.4	1.02	L	T	2290
1.00	0.52	7.82	1.18	310.8	5.32	16.03	1.06	L	T	10380
0.50	0.18	1.58	0.69	427.0	3.26	5.95	0.78	L	T	....
0.03	0.10	0.61	0.51	8898.0	4.07	4.34	0.83	L	T	....
0.42	0.14	1.12	0.95	1896.0	3.70	5.41	0.78	L	T	....
0.20	0.12	1.00	0.99	....	5.44	11.68	1.13	L	T	....
0.57	0.23	1.43	0.68	38.6	2.22	6.29	1.00	L T	T	....
0.29	0.18	0.93	0.57	156.6	3.04	2.33	0.53	L	T	....
0.28	0.08	0.56	0.75	....	5.51	3.33	0.72	L	T	....
0.25	0.23	1.28	0.59	....	6.24	3.96	0.78	L	T	....
0.12	0.09	0.64	0.77	5876.0	3.78	7.39	1.01	L	T	....
0.28	0.14	0.68	0.52	14.8	1.68	3.57	1.00	T	T	....
0.69	0.23	1.45	0.71	547.3	4.04	7.29	1.11	L	T	....
0.48	0.18	0.85	0.52	....	5.89	14.17	1.67	L	T	....

[d]Watershed 110: 1.27 acres, 13.0 per cent average slope, poor practices used as defined below, Keene silt loam.

[e]Watershed 106: 1.56 acres, 14.3 per cent average slope, poor practices used as defined below, Muskingum silt loam.

[f]Watershed 121: 1.42 acres, 15.8 per cent average slope, conservation practices used as defined below, Muskingum silt loam.

(continued)

[g]Watershed 129: 2.71 acres, 18.6 per cent average slope, conservation practices used as defined below, Muskingum silt loam.

[h]Watershed 135: 2.69 acres, 15.3 per cent average slope, poor practices used as defined below, Muskingum silt loam.

[i]Watershed 130: 1.63 acres, 21.7 per cent average slope, conservation practices used as defined below, Muskingum silt loam.

[j]T--turbulent flow; L--laminar flow.

Conservation practices--Contour cultivation, high fertility level, limed to pH 6.8, alfalfa-timothy meadow for two years, in a four-year corn-wheat-meadow rotation.

Poor practices--Straight rows across slope, low fertility level, limed to pH 5.4, no alfalfa in meadows.

Table 2--Velocities of surface flow on plots and watersheds

Date	Area	Slope	Cover			Discharge	
			Type	Height	Density	Rate	Velocity
		pct		in	pct	in/hr	fy/sec
.....	Plot	10.0	Bare	0	0	3.5	0.7
May 22, '41	109	12.7	Bare	0	0	2.04	0.73
May 29, '41	109	12.7	Corn	26	18	3.14	0.89
June 16, '46	103	11.3	Corn	10	6	3.45	0.65
June 16, '46	110	13.0	Corn	10	5	3.73	0.99

slope, the rate of discharge was 3.13 in/hr on July 27, 1948 and the computed velocity 2.14 ft/sec (see Table 1). Column 10 shows that average velocities, v_a, for peak rates of flow tend to decrease as the density of cover increases. For example, in Figure 3, peak rates of flow for the curves whose density of cover values are zero and 80 per cent are 1.27 and 1.75 in/hr, respectively. The average velocities for these rates of flow are 0.57 and 0.38 ft/sec, respectively. Considering the rates of flow, there are decreases in velocities with increases in the density of cover. For this same Watershed 123, Column 9 shows rates of runoff of 1.00 and 1.91 in/hr and velocities of 0.82 and 0.32 ft/sec when the density of wheat was 30 and 88 per cent, respectively.

It may also be observed from Columns 1, 2, 3, and 10 that velocities on a given watershed, for reasonably equal rates of runoff, decrease as cover changes from corn to wheat to meadow. For reasonably similar rates of runoff from Watershed 121 under conservation practices and Watershed 106 in poor practices, velocities are lower on the former. For example, on August 23, 1944, rates of runoff from Watersheds 121 and 106 were 7.82 and 7.63 in/hr, respectively, whereas average velocities were 1.18 and 1.80 ft/sec, respectively.

On a given watershed, the density of cover is an appreciable factor. The rate of runoff was 3.13 in/hr on July 27, 1948 on Watershed 106, corn 33 inches, density 70 per cent. The rate of runoff was 7.63 in/hr on August 23, 1944 on the same watershed, corn 84 inches, density 95 per cent. Even though the rate of flow was twice as great on August 23, 1944, the velocity of flow was 1.80 ft/sec as compared to 2.14 ft/sec on July 27, 1948.

Cover, m, and type of flow--The values of m for various flows on the watersheds are shown in Columns 12 and 14 of Table 1. The type of flow indicated by these values is shown in Columns 15 and 16 of Table 1. Table 3 shows an increase in the value of m as density of cover increases. The first and third values shown in this table are the curves plotted in Figure 3, where m is shown to increase with an increase in the density of cover. Figure 4 shows density of cover plotted against m for Watershed 123, data taken from Table 1. In general this relationship holds for other watersheds. The flow ranges from turbulent for both the rising and falling sides of hydrographs for little cover to laminar flow, for at least the rising side of the hydrograph, for cover of good density. Flow appears to be laminar at a cover density of about 90 per cent and fully turbulent at a cover density of about 18 per cent. Between this range in cover conditions, flow is a mixture of laminar and turbulent.

Cover, rainfall, runoff, flow, and erosion relationships--Table 4 presents relationships involving erosion. Perhaps the most striking entry in this table is the apparent effect of the height and density of cover on erosion. Many investigators have found that land cover greatly influences erosion. Both the height and density indicate the extent to which the soil is protected and the development of roots in their effect in binding the soil. Erosion was by far the greatest under corn

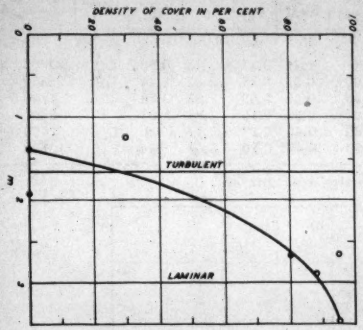


Fig. 4--Relationship of density of cover to m

but materially decreased as corn grew to a height of 92 inches with a density of 68 per cent. Erosion was considerably less under wheat and was the least under meadow. In Table 4, of all the factors affecting erosion, the factor showing the most differences was the cover. In Figure 5 erosion is plotted against density of cover as obtained from Table 4. Only storms of high rainfall rates were used in this comparison.

Dispersion of soil under the high rates of rainfall apparently occurred during the storms of June 16, 1946 and June 20, 1942, when erosion was highest. Transportation of soil by surface flow, which is the measured erosion, seems largely due to the lack of soil-binding power of the sparse vegetation. There are probably three major factors operating in the erosion processes: (1) the dispersion of soil by raindrop impact making soil particles available for movement; (2) their removal by velocity of water in surface detention; and (3) the scouring or pick-up force of surface detention flow and resultant removal. Although rates of rainfall and runoff were high for most of the other storms, (see Table 4), density of crops was considerably higher resulting in less erosion. The least erosion occurred on July 7, 1941 under meadow, even though total rainfall, intensity of rainfall, and total runoff were as great as that for most of the other storms. Factors involved on this date were the greatest density of cover, lowest velocity and rate of runoff, high intensity of rainfall, next to the lowest depth of surface detention, and the lowest index of turbulence. It is possible that these factors are listed somewhat in their order of importance, with density of cover probably the outstanding. It is to be observed that considerable erosion occurred on June 28, 1940 under wheat with a height of 33 inches and a density of 65 per cent. The computed velocity of surface detention was the highest of the six storm periods and the flow index was turbulent on both the rising and falling sides of the hydrograph.

Summary--These studies may be summarized as follows: (1) For identical runoff rates the average depth of detention storage on a watershed on the rising side of the hydrograph was found to be noticeably greater than that for the falling side. The slope of the surface detention and rate of runoff relationship, m, was greater on the rising than on the falling side. Differences were

Table 3--Cover, m, and type of flow relationships

Watershed	Date	Cover			m		Flow type[a]	
		Type	Height	Density	Rise	Fall	Rise	Fall
			in	pct				
123	May 17, '41	Corn	0	0	1.39	0.871	T	T
123	May 22, '41	Corn	0	0	1.93	0.979	L T	T
123	Aug. 15, '41	Corn	80	80	2.67	1.02	L T	T
123	June 16, '46	Wheat	40	88	2.89	0.974	L T	T
123	Apr. 13, '48	Meadow	5	95	3.46	0.345	L	T
109	May 22, '41	Corn	0	0	1.53	0.948	T	T
109	June 29, '41	Corn	26	18	2.04	1.19	L T	T
109	June 28, '40	Wheat	37	68	4.78	1.21	L	T
103	June 16, '46	Corn	10	6	1.46	1.03	T	T
103	June 28, '40	Wheat	38	65	2.29	0.936	L T	T
103	Sep. 23, '45	Meadow	5	72	3.95	0.94	L	T
130	June 16, '46	Permanent meadow	4	50	4.04	1.11	L	T
130	Sep. 23, '45	Permanent meadow	7	86	5.89	1.67	L	T

[a]L = laminar; T = turbulent; underscore indicates predominance.

Table 4--Cover, rainfall, runoff, and erosion relationships for Watershed 110

Date	Cover			Rainfall		Runoff				Flow type[a]	Erosion
	Type	Height	Density	Total	Rate 3 min	Total	D_a	q	v_a		
		in	pct	in	in/hr	in	in	in/hr	ft/sec		lb/sec
June 16, '46	Corn	10	5	3.03	5.80	1.75	0.27	3.73	0.99	L T	33990
June 20, '42	Corn	27	10	0.73	6.00	0.25	0.16	2.82	1.24	L T	25200
July 21, '46	Corn	92	68	1.73	2.90	0.35	0.09	1.25	0.98	T	1840
June 28, '40	Wheat	33	65	1.64	4.80	0.89	0.15	2.87	1.37	T	2500
July 23, '40	Meadow	5	55	1.12	3.80	0.45	0.17	2.47	1.06	L T	2400
July 7, '41	Meadow	6	85	2.00	4.60	0.47	0.10	0.64	0.44	L T	100

[a] L = laminar; T = turbulent; underscore indicates predominance.

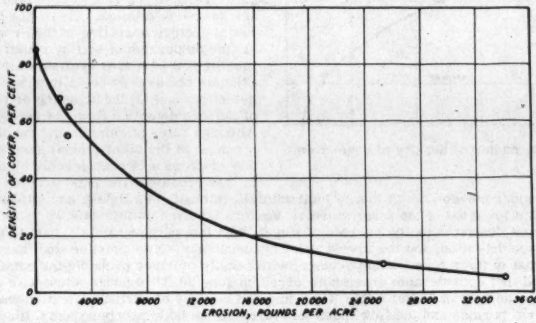


Fig. 5--Density of cover and soil loss relationships for storms of high rainfall rates, Watershed 110

found to decrease for successive peaks of a multiple-peak hydrograph. Apparently the flow of the earlier peaks "lubricate" the watershed and improve hydraulic factors affecting flow.

(2) For identical runoff rates the average depth of detention increased as the density of cover increased. For the same rates of maximum runoff, m appeared to increase as density of cover increased.

(3) Velocities of surface-flow (in detention) computed for watersheds compared favorably with velocities measured on plots, particularly for bare soils and furrows. Velocities of flow decreased as the density of cover increased.

(4) Velocities on a given watershed, for reasonably equal rates of runoff decreased as cover changed from corn to wheat to meadow. As a given cover increased in density, velocities decreased even though rates of runoff increased.

(5) Velocities were lower on watersheds under conservation practices than on watersheds under poor practices.

(6) Values of m indicated that average flow for the watershed appears to be laminar at a cover density of about 90 per cent or greater and fully turbulent at a cover density of about 18 per cent or less. Between this range in cover conditions, flow is a mixture of laminar and turbulent.

(7) Considering factors involved in erosion such as density of cover, velocity and rate of runoff, depth of surface detention, rate of rainfall, and turbulence of flow the most important single factor appeared to be the density of cover. With all these factors high there will be little erosion. With all factors high except density of cover there will be considerable erosion. The soil-binding power of the root system is another important factor. For a number of cover types high density and considerable binding power go together.

Surface detention or overland flow and land use and physiographic relationships were established and related to rates of surface runoff. Such relationships could well be correlated with a hydrologic grouping of soils and climatic provinces. Such information should be beneficial to

programs involving land utilization and the effect of changes in land use. It would seem highly desirable to begin to classify such data and results of analyses. Regardless of the size of watersheds, there are small units of land within such watersheds following hydrologic laws and being integrated by nature into hydrologic performances on land surfaces.

Acknowledgment--Grateful acknowledgment is made to D. E. Hall for assistance in computations and preparation of graphs.

References

SCHIFF, LEONARD, Hydrology of surface suuplies to runoff, U. S. Dept. of Agric., SCS-TP-90, 26 pp., 1950.

HORTON, R. E., Surface runoff phenomena, Part I--Analysis of the hydrograph, Horton Pub. 101, Feb. 1, 1935.

P. O. Box 513,
Bakersfield, California

(Manuscript received April 20, 1950, and, as revised, November 6, 1950; presented at the Thirty-First Annual Meeting, Washington, D. C., May 1, 1950; open for formal discussion until July 1, 1951.)

Transactions, American Geophysical Union Volume 32, Number 1 February 1951

ELECTROTHERMIC RIG FOR THE BORING OF GLACIERS

A. Nizery

Abstract--The electrically heated bit described is used for boring sounding holes in glaciers. The bit, which melts its way downward, is a bare high-resistance wire, helically wound and tapering to a point. Appropriate contacts and relays provide protection when encountering rocks or air spaces. The average drilling speed of the bit was 20 to 25 m/hr for an average hole diameter between 60 and 80 mm. The deepest boring was stopped by bedrock 195 m below the surface of the glacier. Theoretical and practical aspects of the development and use of this apparatus are discussed.

Introduction--The first attempts of boring to determine the thickness of glaciers for scientific purposes go back, in Europe, to 1842. In 1900, the eminent Swiss glaciologist, MERCANTON, used a hand-powered rotating boring rig, which, in the best of conditions, drilled three meters an hour. This kind of boring [FLUSIN, 1909] often associated with geophysical prospecting, has regained interest with the advent of prospecting for the study of sub-glacier water supply for hydroelectric plants in high mountainous country [WAEBER, 1945]. For the development of such projects the engineer must know with sufficient precision the topography of the contact surface of the glacier with the bed-rock.

A short time before the last War, during a reconnaissance of the glacier Mer de Glace near Chamonix, France, Rac-Madoux perfected a hand-powered auger drilling rig which used salt water injection to obviate blocking of the hole by pieces of ice chipped off by the auger. This rig, which was used in a gallery in the ice, could, in practice, drill ten meters per eight-hour shift, including all operations. This rate could have been considerably increased by powering the rig with a motor as has been done with certain Canadian rigs which drill at the rate of about eight meters an hour.

In order to perform reconnaissance operations for the sub-glacier water-tapping projects planned in the French Alps by the Electricité de France, the Service des Etudes et Recherches Hydrauliques (Hydraulic Research Service) was given the task, in 1948, of developing a glacier-sounding device capable of going down to depths 200 to 300 m.

To obtain adequate drilling speeds and reach such depths, the weight of the mechanical equipment and particularly that of the boring rods is a considerable draw-back when transportation difficulties on glaciers and their surroundings are considered. To by-pass these difficulties we developed the idea of drilling with an electrically heated bit vertically downward to bedrock. (After our apparatus was developed we learned that drillings had been performed on the Hosand Glacier by using a drilling bit heated with a stream of hot water supplied by a small wood-heated boiler. Drilling speeds varied between four and ten meters an hour, all operations included [CALCIATI, 1947]. On March 30, 1945, Koechlin patented in France, a drilling device comprising an elongated electrically heated shell suspended by a supply cable and to which he assigned a theoretical drilling speed of 2.07 m/hr.) The "hot drill" is supported by a cable (also used for the electric current) similar to the sounding leads used at sea since ancient times.

Laboratory tests showed that to obtain great drilling speeds it was essential that the electric heating resistance be in direct contact with the ice, no electric insulating material whatsoever being interposed. Development work done both in the laboratory and in the open under the direction of Terrier, Engineer of the Division of "Outside Tests" of the Service des Etudes et Recherches Hydrauliques lead to the realization of the drilling rig we are about to describe. In the course of two drilling programs performed on the Mer de Glace, this apparatus gave average drilling speeds between 20 and 25 m/hr.

Theoretical boring speed of a thermic drill--It is easy to calculate the boring speed V in cm/sec of a thermic drill in ice in terms of the power W in watts dissipated in the form of heat per square centimeter of cross-section of the drilling S. The quantity of heat supplied per second is

$$Q = W/4.18 \text{ gr cal} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

The quantity of heat needed to transform the ice cylinder of height V at 0° C to water at 0° C is expressed by $Q' = 80\ V\ S$ gr cal, the latent heat of fusion of ice being 80 gr cal/gr. In temperate regions observations show that the temperature of the whole of the glacier is very near 0° C except for a surface layer of a few meters thickness which is influenced by the temperature of the air and may be at a lower temperature. This explains why the ice, melted by the hot bit, does not freeze again during drilling.

As the glacier is a very good insulator, heat losses are very small, and we can write

$$Q = Q' = W/4.18 = 80\ V\ S \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

hence

$$V = (1/335)\ W/S \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

$\sigma = W/S$ is the energy per second in watts per square cm of cross section of the drilling. For a drilling speed on one centimeter per second, that is, 36 m/hr, we evidently have $\sigma = W/S = 334.4$ or 335 watts/sq cm which would require a total energy of 25 kw to drill a hole 0.10 m effective diameter, or 6.25 kw to drill a hole 0.05 m effective diameter.

As the average cross-section of the drill-hole S is always a little larger than the cross-section of the heating element, part of the calories are used to widen the hole. To obtain great drilling speeds a heating element giving a high intensity of energy per square centimeter of cross-section is therefore necessary. A liquid or gaseous fuel burner, or an electric arc submerged in the melted ice water, would theoretically give the best answer, but in view of the long delays necessary for the development of such apparatus our efforts were directed toward the use of a high specific-load electric resistance.

Optimum characteristics of the electric heating resistance--Consider a metallic wire of diameter d and resistivity ρ in which carries a current I, surrounded by a fluid, the temperature of which differs from that of the wire by θ° C when a steady state is attained. In a first approximation suppose that the energy dissipated by the lateral surface of the wire is proportional to the current and the temperature difference θ. Under steady state this energy is equal to the Joule effect in the wire. Then

$$A\pi dL\theta = 4\rho L\, I^2/d^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

For the energy $A\theta$ per unit of lateral surface πDL of the wire

$$A\theta = L\rho I^2/\pi^2 d^3 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

In this case the quantity $A\theta$ must be as great as possible in order to obtain a maximum intensity W/S. This quantity however is determined by the necessity of not heating the resistance to a temperature higher than that which insures an acceptable service life. In order to reduce electric current current to a minimum under these conditions we must select (1) a metal of resistivity ρ as great as possible; and (2) a wire of diameter d as small as possible. In this line we are limited by requirements of mechanical resistance and electrical insulation of the heating element which must be in direct contact with the ice and its water of fusion.)

The above calculation which applies to any heating resistance will enable us to show the high values of energy used by the drilling bit per square centimeter of lateral surface of the resistance wire under working conditions. Our laboratory tests showed that available heating elements made of a resistance protected by a metallic tube and insulated from the latter by a magnesium salt filling (Calrod type) in contact with the ice and the water melted by the drill could not support specific loads above 15 watts/sq cm of lateral surface. The bare Tophet wire of 1.63 mm diameter, which is used as heating element in our drilling bit, resists ten times greater loads with a good security margin. (An electric resistance made of metallic tape would allow higher specific loads than one made of wire; but the low mechanical resistance of the small sections involved here results in difficulties.) In general, an insulated resistance thermoelectric drilling bit will give drilling speeds of about one-tenth those obtained with a bare wire resistance. As indicated earlier, the drilling speed of the bit is not a direct function of the energy $A\theta$ per unit of lateral surface of the resistance wire, but of the intensity of energy per square centimeter ($\sigma = W/S$) of cross-section of the

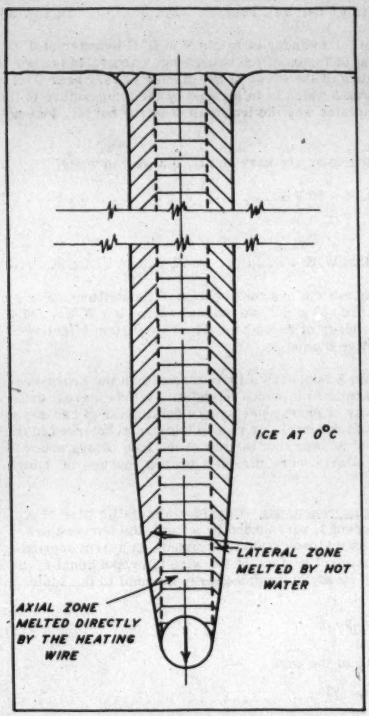


Fig. 1--Schematic profile of the cutting made in ice by a straight heating wire F perpendicular to plane of the figure

hole. It is therefore beneficial to concentrate the energy in the direction of the drilling, limiting as far as possible the difference between the effective diameter of the drilling and that of the heating element of the drilling bit. The following experiment gives some indications of the steps to be taken.

Let us consider a straight horizontal heating resistance wire with a long contact length along the lower part of the circumference of its cross section with a block (see Fig. 1) of ice. Observations show that the melting of the ice first takes place at the direct contact of the wire which progressively goes down through the block. About the wire we find a hot water zone where violent convective movements take place and widen the cutting made by the wire by melting its sides. This action stops when the water cools back to ice melting temperature. Finally, within the conditions of our experiments, the cutting produced by the wire has a profile of two parallel lips separated by about twice the diameter of the wire, approaching each other at the bottom of the semicircular hole by two parabolic-shaped curves.

This schematic mechanism of fusion led us to conceive a heating resistance made up of resistance wire helically wound round the surface of a cone, the angle at the apex of the latter and the helix pitch being selected so that the distance between two consecutive turns be such that the action zone of the higher turn does not overlap with that of the lower one, this action being defined by the above described experiment. In practice we were obliged to modify these conditions to a certain extent for they would have required the resistance to conform to an apex cone too acute for the system to conform with necessary strength and simplicity. This probably explains why, with maximum diameter of the resistance being 50 mm, the drill-holes showed an average diameter of 70 to 80 mm.

Description of the electrothermic boring rig--The apparatus consists of (1) a drilling bit body including the heating resistance and its protection contacts; (2) a very flexible rubber cable supporting the bit body and including two conductor wires for the heating resistance and two pilot wires for the protection of the latter; (3) a derrick made of metal tubes supporting the winding system of the cable (controlled by a capstan driven by a variable speed electric motor) and the operation and control panel; and (4) the electric generating set or sets.

Figure 2 shows the assembled apparatus set up on the Mer de Glace. Figure 3 shows details of the drilling bit and of the capstan for the winding of the suspension and supply cables.

The bit body is made up of a hollow brass cylinder 50 mm exterior diameter and one meter long; its weight, including the lead ballast it contains, is about 15 kg.

The heating resistance is made up by a Tophet A wire 1.63 mm diameter and one meter long, wound on a conical helical path, the maximum diameter of which is 50 mm. The ends of the resistance are attached to the electrodes inside the bit body by connection screws in order to provide quick replacement of a resistance in case of accident. The resistance, which is about 0.54 ohms, takes 120 amperes in normal service, at a potential of 65 volts. The power is thus 7.8 kw.

Fig. 2--General view of the drilling rig erected on the Mer de Glace near Chamonix, France

Fig. 3--Detail of the bit-body and driving capstan

Suspension and supply cable in the apparatus used in 1948 and 1949 was two very flexible 30 sq mm copper cables strongly insulated with rubber (particularly to resist ice abrasion during operations) from which the bit body was suspended. The weight of each cable was 0.50 kg; and the resistance of each was 6×10^{-4} ohms/m. In the future, we intend using a single cable including the two 30 sq mm principal conductors and the two pilot wires for the protection of the resistance.

The three-legged metallic derrick and the head sheave of the suspension cable were made to have least weight and maximum strength. The cable is wound in one or two coils on the capstan pulley controlled by a worm gear through a direct current variable speed electric motor having 0.5 HP. The driving of the cable automatically stops through lack of contact of the coils on the capstan as soon as the drilling bit resting at the bottom of the hole, and no longer exerts pull on the cable.

The power needed for the drill and its equipment (capstan, lighting) is ten kilowatts. As the equipment is to be transported on the ice by only man, the weight must be reduced to a minimum, not only the total weight but also the weight of the heaviest piece that cannot be dismantled. During the drilling on the Mer de Glace in 1949, we used two electric generating sets arranged in parallel, each made up of a four-cylinder air-cooled gasoline engine coupled by a belt with an 80-volt, 60-ampere direct-current generator. The rated speed of the generators was 2200 rpm. The weight of one electric generating set was 150 kg; its gasoline consumption was about five liters per hour. In reducing the weight of the electric generating sets to a minimum, it must be kept in mind that the equipment must be strong enough to withstand the severe working and moving conditoins that are met on a glacier for days at a time.

The electric resistance can support the high specific loads indicated above only because of the cooling effect of the ice and strong convection currents in the melted ice water it produces. Without protection it would soon get out of order in the following two circumstances which occur in the course of drilling: (1) The resistance emerges in a crevasse or an air-pocket. The water

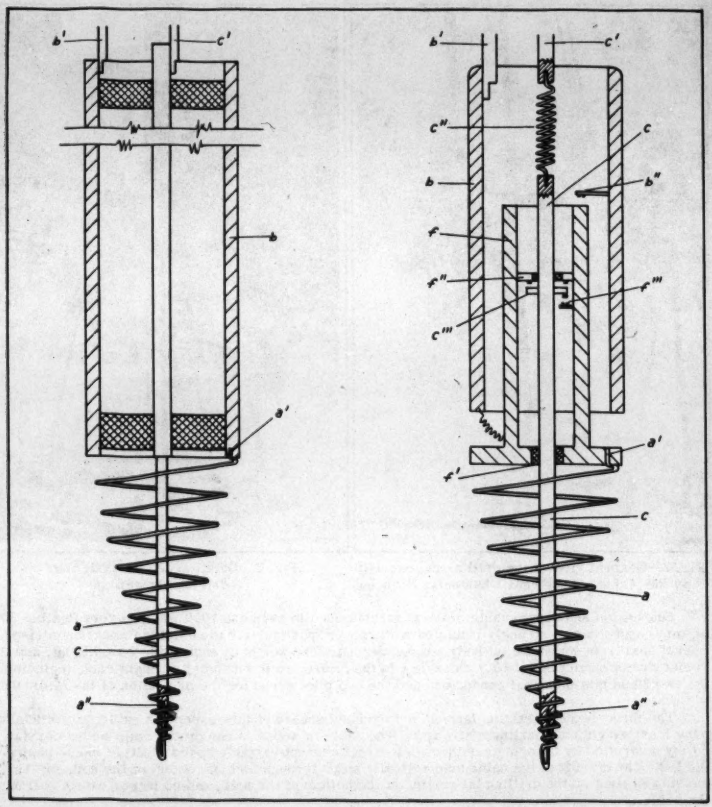


Fig. 4--Section of the bit-body showing the device for protection of heating resistance

of fusion which normally fills the drilling drops out and the resistance would only have air to cool it and would seen melt. (2) The bit meets a stone or contacts the rock. In this case the convection currents of the water can be insufficient to prevent melting of the resistance after a time.

To obviate the damage that might result, the resistance in thrown out of circuit automatically by the device shown in Figure 4. Inside cylinder b, suspended from the electric cable is a sleeve f, to which is connected the upper end a' of the resistance a. Rod c, to the lower part of which is connected the lower end of the resistance a", can slide in sleeve f through electric insulators such as f'. Rod c which is suspended from conductor c' by a flexible conductor c", has a buffer c''' which presses on buffer f" of sleeve f, when the apex of the resistance is in contact with the ice.

When the end of the bit emerges in an air pocket, rod c is no longer pressed against buffer f", its weight makes it descent rapidly because of the great elasticity of the resistance which is increased by its temperature. Buffer c''' on rod c then comes in contact with f''' held by f. This contact closes the circuit on a current source g (see Fig. 5) on an instantaneous

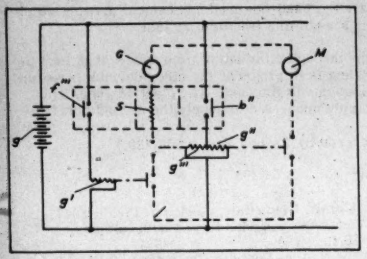


Fig. 5--Electric scheme of the protection device of heating resistance

relay g' which cuts off the circuit of the supply G of the bit shown at S. The delay is one or two seconds. For this period, the water running out into the air pocket is enough to keep the extra heating of the resistance within safe limits.

When the bit stops going down, for instance by hitting a stone, cylinder b continues to go down; sleeve f then closes contact b'' held by cylinder b. This contact closes the circuit of source g on both the instantaneous relay g'' which cuts the supply to motor M for lowering the bit and the time relay which cuts the circuit of supply G with a delay of ten to 20 sec. The motor lowering the bit is stopped immediately to prevent the whole weight of the cable from compressing the resistance, at a time when cooling is deficient.

First uses of the electrothermic boring rig--The first trial tests on the Mer de Glace in 1948 demonstrated the good working order of the rig. A drilling program was undertaken on that glacier between July and October 1949 as part of reconnaissance work of an electric equipment project of the Region d'Equipement Alpes II of Electricité de France for sub-glacier water supply of a hydroelectric plant. The object of the drillings was to determine two cross sections of the glacier. The first cross-section, named Montenvers, was about 570 m wide at the surface (altitude 1815 m). The second, Allée Verte, is located one kilometer up the valley and is about 900 m wide (altitude about 1950 m). On the Montenvers cross-section 14 holes totalling 950 m were drilled. The deepest hole was stopped by the bedrock 195 m below the surface of the glacier. On the Allée Verte cross-section seven holes of approximately equal depth and totaling 450 m were drilled.

The following are the principal observations made during this work. The average drilling speed was 20 to 25 m/hr; the average diameter of the holes varies between 60 and 80 mm for a maximum heating-resistance diameter of 50 mm. (For a drilling 70 mm in diameter, the power density, $\sigma = W/S$ was 7800/38.5, or approximately 200 watts per sq cm of drilling cross-section.) Normally the hole stays full of water which does not freeze again, even several days after drilling.

When going through a crack or an air-pocket, the time the hole takes to empty is sufficient to be able to put the heating resistance out of circuit manually. The automatic protection made for that purpose is therefore not absolutely necessary. When the drilling is continued after the water has thus been emptied, current intensity for the heating resistance must not be above that dangerous for the element when it is in air until sufficient water has formed again to surround it. Beginning during the good season (July-August), glacier cracks have running streams of water in them, which sometimes cause overflowing of the drill hole at the surface of the glacier. Emptying of the drill holes appeared less frequently than in the later season (October), during which water circulation through the glacier is hampered or stopped by freezing. Drillings were sometimes stopped by isolated stones which appear irregularly in the glacier but which become extremely rare 20 m below the surface. When meeting small stones the bit can sometimes either push them aside or go round them. To go through the bigger stones, a mechanical drilling device must be used. Getting through thin sand beds with the thermic bit is sometimes possible with a little deterioration of the heating resistance caused by less cooling. The top of the hole must be protected from gravel and sand which might be washed into it by running water on the glacier. When the hole reaches the bedrock it usually empties and the sub-glacier stream can sometimes be heard. Continuity of the cross-section usually helps in determining whether the bedrock or a rock embedded in the glacier has been reached.

Verticality of the holes seemed satisfactory; it will be checked in the course of the next drillings by clinometer measurements. Naturally the hole gets out of shape because of the movement of the glacier (about 0.12 m a day at the surface on the Mer de Glace). Each hole must therefore be done without interruption and as quickly as possible.

The operation of the rig requires two men. One standing at the control panel fixed on the derrick, can stop the motors of the electric generating sets with a circuit breaker on the sparking circuit. The other attends the electric generators, makes cable connections, and related work. This

represents a great man-power saving when compared to hand-powered mechanical drilling which requires three to four times more men for drilling a tenth to a twentieth as fast.

In order to speed the plotting of cross-sections through eliminating time waste, it is best to have two derricks and drilling bits. While one drilling is in progress the other derrick is set up on the next site, to be started as soon as the previous one is finished. The electric generating sets (in principle set up at a fixed place) can be simply connected to supply the second derrick.

Patent--This rig and its appurtenances are covered by French Patent 566,289.

References

CALCIATI, M., Boring of the Hosand glacier, Boll. Comit. Glac. Ital., v. 24, pp. 17-20, 1947.
FLUSIN, G., Glaciers boring at depths, Service d'études des grandes forces hydrauliques, Etudes Glaciologiques, v. 1, pp. 5-31 + 9 pl. + 26 fig., 1909.
WAEBER, M., Sub-glacier water tapping at Tré-la-Tête, Ann. Ponts et Chaussées, Juillet-Août, pp. 438-460, 1945.

Service des Etudes et Recherches Hydrauliques,
Electricité de France,
Paris, France

(Manuscript received April 4, 1950; presented at the Thirty-First Annual Meeting, Washington, D. C., May 2, 1950; open for formal discussion until July 1, 1951.)

Transactions, American Geophysical Union Volume 32, Number 1 February 1951

STREAM-FLOW FREQUENCY CHANGES ON COWEETA EXPERIMENTAL WATERSHEDS

J. A. Lieberman and M. D. Hoover

Abstract--Three land-use changes were made on small watersheds at the Coweeta Hydrologic Laboratory as follows: (1) removal of all major forest vegetation with repeated cutting of sprout growth; (2) removal of all major forest vegetation with natural regrowth allowed; (3) removal of all major forest vegetation and placement of the area under agriculture. The streamflow effects are demonstrated graphically by comparing frequency distribution curves of daily flow for periods before and after changes in land use. For the same periods comparisons are also made with similar curves for control watersheds on which no land-use changes were made. The ratios of the flows exceeded 16 per cent of the time to the flows exceeded 84 per cent of the time are presented as indexes of variability of streamflow. Each of the changes in land use resulted in increases in mean daily discharge when the rate of flow was below about three cubic feet per second per square mile. The higher base flow is attributed to the reduction in transpiration draft.

Introduction--Frequency distribution curves of mean daily discharge from treated experimental watersheds on the Coweeta Experimental Forest are compared for the prior and post treatment periods. In addition, similar comparisons are made between each treated watershed and an untreated, or control, watershed. From these comparisons conclusions are drawn as to the effect of the treatments on the regimen of daily stream flow and as to the practicability of frequency distribution curves in showing stream-flow changes brought about by experimental land use treatments.

The Coweeta Experimental Forest is a 5500-ac hydrologic research area operated by the Southeastern Forest Experiment Station of the U. S. Forest Service. Previous papers [see References] have given a description of the area and some results of watershed studies in progress. Table 1 gives a summary of rainfall, runoff, and temperature for one of the untreated experimental watersheds which is generally representative of the area.

Table 1--Average monthly precipitation, runoff, and air temperature for the period 1936 to 1945, Coweeta Watershed 18

Month	Precipitation	Runoff		Air temperature
	inch	inch	pct	°F
Nov.	4.32	1.10	25.5	43.9
Dec.	7.24	1.93	26.7	38.8
Jan.	5.79	3.37	58.2	38.1
Feb.	7.50	4.83	64.4	39.9
Mar.	7.64	5.41	70.8	47.3
Apr.	5.89	4.76	80.8	56.4
May	4.21	3.47	82.4	64.1
June	4.56	2.09	45.8	71.1
July	7.34	1.93	26.3	72.0
Aug.	5.76	1.66	28.8	71.5
Sep.	4.41	1.19	27.0	65.6
Oct.	3.08	0.94	30.5	55.8
Totals and mean	67.74	32.68	..	55.4

Experimental watershed treatments--One of the research objectives at Coweeta is to determine the effect of various land-use treatments on stream flow. To accomplish this, treatments are actually carried out on individual drainage areas, and the effects measured. The treatments under consideration in this paper are:

(1) All the vegetation on the 33-ac Watershed 17 was cut during January-March 1941 after a five-year calibration period. No material was removed. Trees were left where they fell and tops and limbs were lapped and scattered uniformly over the ground surface to form a loose mulch. This mulch protected the soil against excessive drying by sun and wind and maintained the forest soil. Sprout growth was cut back in the summers of 1941 and 1942, winter of 1946-1947, and summer of 1947. The adjacent 31-ac Watershed 18 which remained in natural forest cover serves as a control for this treatment.

(2) Watershed 13, an area of 40 ac, was cut over as described for Watershed 17 during the winter of 1939-1940. Natural re-growth has taken place since that time. Sprouts have developed rapidly and there are now 800 stems per acre

which are larger than two inches in diameter and average over 20 ft high. This watershed is compared with the nearby 31-ac Watershed 2 which has been undisturbed.

(3) The 23-ac Watershed 3 was cleared for agricultural use during the winter of 1939-1940. All vegetation was cut and stumps less than 17 inches were pulled. The logs were removed and the brush and tops were piled around the large stumps and burned. In 1941, 1942, 1943, 1946, and 1947 a six-acre portion of the area was cultivated for corn and the remainder was pastured by cattle. This watershed is also compared with the 31-ac Watershed 2.

Data analysis and results--As a routine compilation procedure, the mean daily stream flow in cubic feet per second per square mile (csm) from all watersheds is determined from continuously recorded stream hydrographs. In this analysis the mean daily stream-flow data from the treated and control watersheds for the total prior and total post treatment periods are grouped and plotted on logarithmic probability paper to present a graphical picture of the frequency distribution (see Fig. 1-3). An inspection of these graphs indicates that the treatments described produced changes in this frequency distribution.

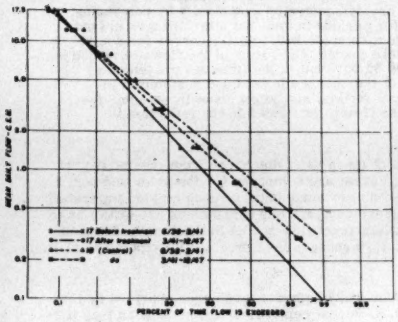

MEAN DAILY FLOW - C.S.M.
PERCENT OF TIME FLOW IS EXCEEDED
17 Before treatment 6/39-5/41
17 After treatment 5/41-12/47
18 (Control) 6/39-5/41
do 5/41-12/47

Fig. 1--Coweeta 17 and 18, flow frequency distribution

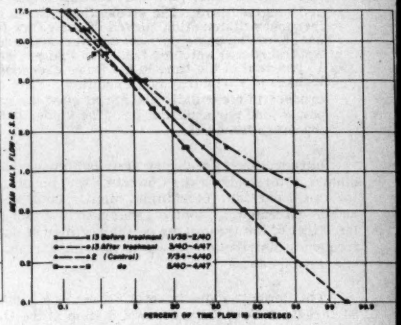

MEAN DAILY FLOW - C.S.M.
PERCENT OF TIME FLOW IS EXCEEDED
13 Before treatment 11/39-5/40
13 After treatment 5/40-6/47
2 (Control) 7/34-6/40
do 5/40-6/47

Fig. 2--Coweeta 13 and 2, flow frequency distribution

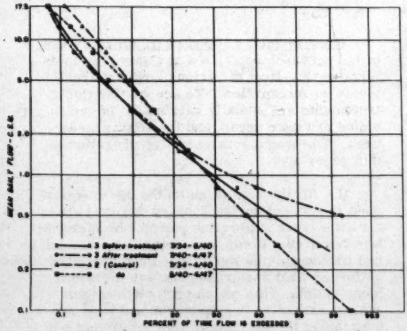

MEAN DAILY FLOW - C.S.M.
PERCENT OF TIME FLOW IS EXCEEDED
3 Before treatment 7/34-5/40
3 After treatment 5/40-6/47
2 (Control) 7/34-6/40
do 5/40-6/47

Fig. 3--Coweeta 3 and 2, flow frequency distribution

Besides the direct visual comparison of the logarithmic probability curves, the comparison of certain ratios and constants obtained from the curves offers a quick and useful means of describing or indicating the general level and variability of mean daily stream flow. The value of the 50 per cent ordinate is taken from the curve to indicate the general level of stream flow, and the ratio of the 16 per cent ordinate to the 84 per cent ordinate is arbitrarily used to describe the variability of the flow. Table 2 gives these values for the watersheds. The ratio of the 16 per cent ordinate to the 84 per cent ordinate is suggested as a more satisfactory indication of variability than the standard deviation because of the skewness of stream-flow data.

On Coweeta 17, where all vegetation was cut, and regrowth also cut, the general level of stream flow was raised, with the most noticeable increase occurring in the lower range of flows. The mean daily flow at the 84 per cent level was increased 124 per cent and at the 16 per cent ordinate, 45 per cent. The median value was increased 83 per cent. Changes in flows above five

Table 2--Comparison of flow frequency distribution curves

Coweeta Watershed	Mean discharge	50 pct ordinate	84 pct ordinate	16 pct ordinate	Ratio, 16 pct ÷ 84 pct ordinate
	csm	csm	csm	csm	
17[b]	1.94	0.88	0.34	2.28	6.71
17[a]	2.74	1.61	0.76	3.30	4.34
18[b]	2.42	1.30	0.58	2.90	5.00
18[a]	2.43	1.30	0.58	2.90	5.00
13[b]	2.51	1.28	0.67	3.00	4.48
13[a]	3.16	1.81	1.08	3.50	3.24
3[b]	1.73	0.97	0.55	1.80	3.27
3[a]	1.93	1.12	0.77	1.87	2.43
2[b]	1.92	0.86	0.36	2.30	6.39
2[a]	1.86	0.86	0.36	2.30	6.39

[a]After treatment period.
[b]Before treatment period.

csm do not seem to be significant. The frequency distribution for control watershed 18 is essentially the same for both the before and after treatment periods, indicating that the changes on watershed 17 are due primarily to treatment and not to climatological changes. A more detailed analysis of the increase in water yield brought about by this treatment has already been made [LIEBERMAN, 1947].

Where natural regrowth was allowed to take place (Watershed 13), the influence of vegetation removal is still evident, although to a lesser degree. The median value shows an average increase of 41 per cent since treatment, with the 84 per cent ordinate increased 62 per cent and the 16 per cent ordinate increased 17 per cent. There is apparently no change in the higher flows. For both this treatment and that on Watershed 17, the values given are the separate averages for the entire prior and post treatment periods. Because of rapid re-establishment of vegetation, greater increases in stream flow occur in the first years after cutting than in later years. An analysis of mean daily discharge on an annual basis would show how the maximum effect of treatment is influenced by regrowth of vegetation.

On Watershed 3, which was cleared for mountain agriculture, a smaller increase in flow was observed than where the forest soil was protected by a mulch. The median value was increased 15 per cent. The value of the 84 per cent ordinate was increased 40 per cent and that of the 16 per cent ordinate shows no significant increase. The reason for the smaller increase in this experiment is believed due to the greater evaporation from the bare soil as compared to the cutting experiments where the brush mulch and the undisturbed forest floor protect the soil.

It must be emphasized that, in this agricultural watershed, the analysis based on mean daily discharge does not give the complete picture of the results of treatment. An important treatment effect has been that runoff peaks from summer thunderstorms have been greatly increased because of the reduction of infiltration rates on this watershed. The time base of the storm hydrographs from this particular watershed is so short that the cognizance of this effect is greatly reduced when the analysis is made on the 24-hr basis of mean daily stream flow. An analysis of peak runoff rates is required to completely evaluate all the results of this treatment.

Discussion and conclusion--In each watershed study in which the major vegetation was cut, the mean daily flows in the range up to four or five csm were increased. These increases can be attributed to the elimination of the transpiration draft of the vegetation and the resulting increased recharge to ground water, which in turn has contributed to high base flows towards the end of the growing season.

Several factors of hydrological importance should be emphasized in connection with the vegetation cutting experiments. First, the fact that none of the cut vegetation was actually removed from the individual experimental area insured minimum soil disturbance. Also, since the cut vegetation formed a mulch over the entire area, the favorable original forest soil characteristics of high infiltration capacities and storage capacities within the soil mass were maintained, and no surface runoff occurred. Second, the rather uniform distribution of precipitation throughout the year is an important factor contributing to the indicated increase in stream flow. Because all the moisture supplied by summer rainfall is not drawn on for current transpiration requirements, a

larger amount of water becomes available for increased base flow. The higher mean daily flows (above five csm) are unaffected because they generally occur in late winter or early spring when storage of soil moisture is at a maximum and approximately the same on all watersheds regardless of the vegetative cover. Thus both treated and untreated watersheds react similarly to precipitation at these times.

The extreme importance of the role played by the soil in the hydrologic picture should also be stressed in connection with the experiment on mountain agriculture. In this experiment increases in water yield are noted, but, in contrast to the areas where the vegetation was not removed, there was also an increase in instantaneous flood peaks and soil movement. The latter may be attributed to a breakdown of soil structure and subsequent decrease in infiltration capacity, pore space, and moisture storage capacity.

The comparison fo flow frequency distribution curves as plotted on logarithmic probability paper and arbitrary values obtained from them afford a useful means of comparing sets of streamflow data and determining some of the influences of land management on the flow of small streams. Although the use of mean daily flow limits the ability to describe hydrologic processes connected with individual storms, these curves represent an additional tool for demonstrating more completely the effects of land use changes on stream flow.

References

LIEBERMAN, J. A., Water resource and watershed management research in the southeast, J. Amer. Water Works Assoc., v. 39, pp. 443-454, May 1947.

LIEBERMAN, J. A., and P. W. FLETCHER, Further studies of the balanced water cycle on experimental watersheds, Trans. Amer. Geophys. Union, v. 28, pp. 421-424, 1947.

HOOVER, M. D., Effect of removal of forest vegetation upon water yields, Trans. Amer. Geophys. Union, v. 6, pp. 969-977, 1944.

HURSH, C. R., and E. F. BRATER, Separating storm hydrographs from small drainage areas into surface and subsurface flow, Trans. Amer. Geophys. Union, 22nd Annual Meeting, pt. 3, pp. 863-871, 1941.

HURSH, C. R., M. D. HOOVER, and P. W. FLETCHER, Studies in the balanced water economy of experimental drainage areas, Trans. Amer. Geophys. Union, pt. 2, pp. 509-517, 1942.

1016 Tod Street (J.A.L.),
Falls Church, Virginia

Southeastern Forest Experiment Station (M.D.H.),
P. O. Box 257,
Union, South Carolina

(Manuscript received December 1, 1948, and, as revised, August 24, 1950; presented at the Twenty-Ninth Annual Meeting, Washington, D. C., April 22, 1948; open for formal discussion until July 1, 1951.)

Transactions, American Geophysical Union Volume 32, Number 1 February 1951

THE ELEMENTARY THEORY OF SUBSURFACE STRUCTURAL CONTOURING

John W. Harrington

Abstract--A system of analyzing subsurface data is developed through the use of a new method of graphical division and based on the recognition of special cases where more than three adjacent points lie on the same geometrical plane or nearly planar surface. These surfaces are then used to control the strikes of preliminary contours. The planes are also used in conjunction with cross sections to establish correction data for the placement of final contours. The uses of the system in drawing a new map and in the evaluation of pre-existing maps are demonstrated.

Introduction--Surprisingly enough there is at best only a very meager literature on the technique of drawing structural contours. The standard handbooks and texts of field and structural geology give the general procedures of the mechanical division, parallel alignment, and equal slope methods. Most recently LOW [1949] has outlined some excellent suggestions on contouring as an interpretative art. There are, however, several definite mechanical steps which may be performed and will by minimizing the intuitive process add authority to an interpretation. They may also be used to evaluate a pre-existing structural map.

A scale for mechanical division--Accurate mechanical division may be accomplished quite easily by use of the scale shown in Figure 1. The technique for its use is much like the standard drafting method for dividing the space between two points into any number of equal parts. The diagram illustrates the use of the scale in placing ten-foot contour spacings between point A at a -652 ft datum and B at a -738 ft datum. The significant digits 5.2 on the scale are placed over A. One edge of the triangle is aligned with B and the significant digits 3.8 on the scale. The various ten-foot elevation divisions are then determined by sliding the triangle across the scale divisions while maintaining parallel orientation. The elevation of any point such as K may be determined by reading the significant digits 7.2 on the scale and converting to the proper hundred on the basis of position right or left of the zero. The elevation of K is -672 ft datum.

The problem of evaluating subsurface structural data--Figure 2 is a diagram of a typical slope following the well recognized form of the family of curves to which parts of all anticlinal and synclinal profiles belong. One objection to mechanical spacing of contours is that it will not reproduce the true pattern shown in the map view of the slope. Figure 3a is an illustration of another objection to mechanical spacing in that there is no assurance that point 0 defines the true crest of the anticline. In order to select the more probable interpretation from Figure 3b, c,

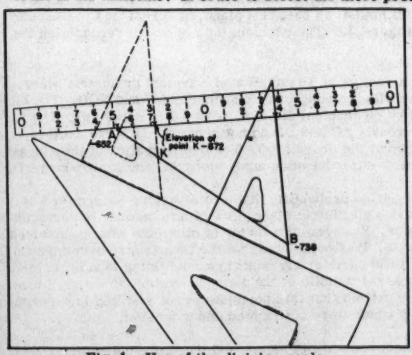


Fig. 1--Use of the division scale

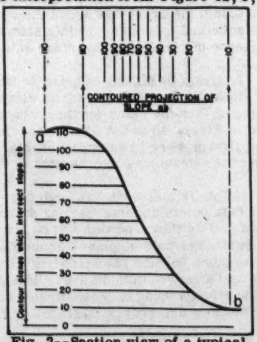


Fig. 2--Section view of a typical slope curve

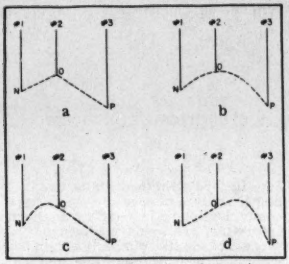


Fig. 3--Interpretations of structure based on the same data points.

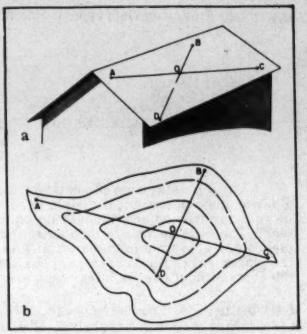
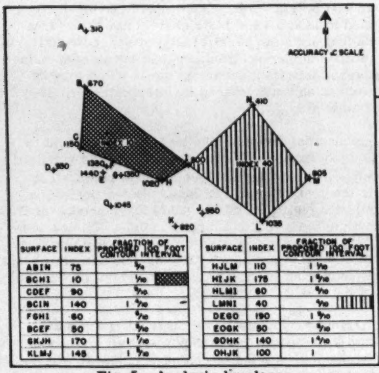


Fig. 4--(a) Intersecting diagonals on a geometric plane; (b) non-intersecting diagonals on a curved surface



SURFACE	INDEX	FRACTION OF PROPOSED 100 FOOT CONTOUR INTERVAL
ABIN	75	3/4
BCHI	10	1/10
CDEF	90	9/10
BCIN	140	1 4/10
FGHI	60	6/10
BCEF	80	8/10
GHJN	170	1 7/10
KLMJ	145	1 4/10

SURFACE	INDEX	FRACTION OF PROPOSED 100 FOOT CONTOUR INTERVAL
HJLM	110	1 1/10
MIJK	175	1 7/10
HLMI	80	8/10
LMNI	40	4/10
DEBO	190	1 9/10
EOGK	80	8/10
GOHK	140	1 4/10
OHJK	100	1

Fig. 5--Analysis by planes

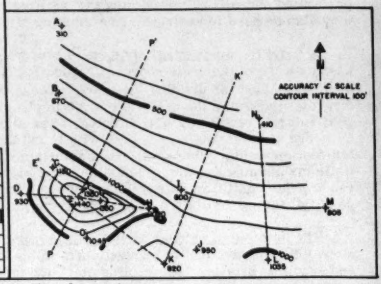


Fig. 6--Preliminary structure contour map

and d it is necessary to distinguish the relative validity of slopes NO and OP. If either is part of a plane, the crest lies above the other. If neither is part of a plane, the crest lies in the central zone and may be spread as shown in Figure 3b. The problem then is one of recognizing the presence of planes in subsurface data.

Analysis by planes--Figure 4a shows a roof as an illustration of a typical geometric plane. Points A, B, C, and D are known elevations with the connecting diagonals AOC and BOD. The elevation of O is the same whether measured by mechanical division along AC or along BD. The surface in Figure 4b is not a plane and the diagonals AC and BD do not actually touch one another even though there is an apparent intersection at the crossing O. The determination of the elevation at the imaginary intersection is therefore different when made along AC and again along BD.

No statistical work has been done to show the probability that a fold surface determined by four data points and intersecting diagonals is a geometric plane. An infinite number of surfaces could satisfy this condition and be non-planar. However, if a factor of minimum area is involved the surfaces would be planes or nearly planar. It is postulated that the tensile stress components set up along bedding planes during orogenic and particularly supratenuous folding tend to maintain surfaces of minimum area. In each case the validity of the diagonal system of analysis rests on the effectiveness of these stresses. It is evident that this postulate is not justified for irregular features like erosion surfaces and reefs which were not formed under tension.

True geometric planes of any areal extent are rare in nature and therefore determinations of exactly the same elevation for intersection will be rare. Determinations which are nearly equal

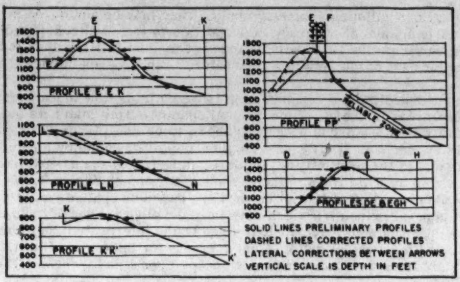


Fig. 7--Determination of correction profiles

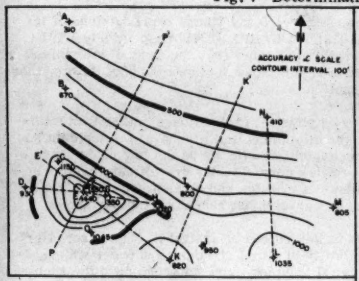


Fig. 8--Final structure contour map

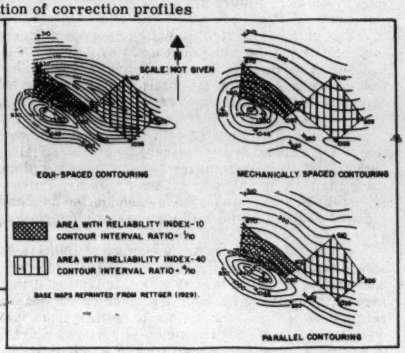


Fig. 9--Evaluation of pre-existing subsurface structure contour map through analysis by planes

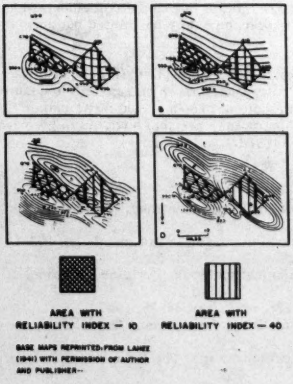


Fig. 10--Evaluation of pre-existing subsurface structure contour map through analysis by planes

will designate surfaces which are nearly planar. Determinations which are markedly unequal show that the surface has great curvature and does not approach a plane. These elevation differences, measured in feet, may be used as a reliability index. A zero index represents a geometric plane. Indices of less than a third the contour interval suggest that mechanical spacing would not produce too significant an error in the placement of contours. Indices above half the contour interval imply that mechanical spacing would be quite inaccurate.

The basis for the recognition of indices lies in the fact that the elevations of the imaginary intersections involve all the factors of data point elevations, slope, and geographical position which are known about the surface. However, variations in the relative sizes of the quadrilaterals reduce the indices to a quantitative value.

Application of the analysis by planes--In Figure 5 a set of data taken from RETTGER [1929] has been divided into a series of test surfaces by diagonals. One of these has an index to contour interval ratio of one-tenth. Another has a ratio of four-tenths. Both

are shaded on the diagram in distinguishing symbols. They may be contoured by mechanical division with a reasonable amount of accuracy in proportion to their indices. Special note should be taken of overlapping surfaces like BCHI with an index of ten and FGHI with an index of 90. This indicates that the major part of the high index curvature is in the area outside the overlap.

The preparation of a preliminary contour map is begun in the low index areas and carried from them to the high index areas by means of mechanical spacing. This map sets out the problem of evaluating the structure in those areas which are known to be non-planar and have therefore been mapped inaccurately by mechanical division. Further analysis is done by means of selected cross profiles oriented normal to the preliminary contours, as shown by the dashed lines on Figure 6. These profiles are shown as solid lines in the various diagrams of Figure 7. More probable corrected profiles are shown as dashed lines. These were based on evaluations of the reliability of slopes following the general principles which have been developed. The arrows indicate the amount of horizontal shifting necessary to place contour lines in the interpreted positions. This shifting is done at the expense of mechanical division and corrects for the error of initial assumptions that all slopes were straight lines and that data points occupy crests and troughs. The final contour map is shown in Figure 8.

Use of the method to evaluate pre-existing maps--Figures 9 and 10 are reproductions of interpretations of the same data made by RETTGER [1929] and LAHEE [1941] respectively. The outlines of the nearly planar surfaces have been shaded on the maps over the work of the author. Comparisons of each of the interpretations on the basis of low index surfaces support those authors' conclusions that their most irregular maps are probably in error.

Summary--Contouring with interpretations based on physical probabilities rather than intuition is possible by following these basic steps: (1) determine the reliability indices of the data surfaces; (2) draw a preliminary map on the basis of mechanical spacing using the low index areas to guide the pattern; (3) make all the necessary cross profiles normal to the preliminary contours; (4) establish correction factors based on the adjustments of profiles and determined by the reliability of slopes; and (5) with the spacings determined by corrections, recontour the surface.

Conclusions--There are a number of limitations to the method of analysis. It does not offer a resolving power great enough to eliminate the possibility of small structures between widely spaced data points. There is no minimization of the vital need for more control, since the accuracy of the final map is still dependent on the density distribution of data. There is no special recognition of the distortion due to faulting from that of any other type of irregularity. It will not distinguish true planes from curved surfaces which have low indices due to the coincidental location of data. The theoretical value of a reliability index is determined by postulated but unproven response of the structural form to tensil stress.

The chief advantage of the system is that it places for first consideration all data that are known. Forms are built on these facts and only then are alterations based on reasonable quantitative corrections added. The final shapes are developed in spite of preconceived ideas rather than because of them. If the limitations are observed, the geologist may use this analysis to give authority to his own interpretations and to evaluate the work of others.

References

LAHEE, FREDRIC H., Field geology, 4th Edition, McGraw-Hill Book Company, Inc., New York, New York, pp. 626-658, 1941.

LEY, HENRY H., Structure contouring, Bull. Amer. Assoc. Petr. Geol., v. 14, no. 1, pp. 103-105, 1930.

LOW, JULIAN, Suggestions on contouring subsurface geological methods, Q. Colorado School of Mines, v. 44, no. 3, pp. 627-657, 1949.

REITLER, W. A., Contouring fault planes, World Oil, v. 126, no. 7, pp. 34-35, 1947.

RETTGER, R. E., On specifying the type of structural contouring, Bull. Amer. Assoc. Petr. Geol., v. 13, pp. 1559-1560, 1929.

STEPHENSON, E. A., and D. D. HAINES, Preparation of contour maps, The Oil and Gas Journal, v. 45, no. 15, pp. 115, 1946.

WHARTON, JAY B., JR., Isopachous maps of sand reservoirs, Bull. Amer. Assoc. Petr. Geol., v. 32, pt. 2, pp. 1331-1339, 1948.

Southern Methodist University, Dallas, Texas

(Manuscript received March 6, 1950; presented at the Thirty-First Annual Meeting, Washington, D. C., May 3, 1950; open for formal discussion until July 1, 1951.)

Transactions, American Geophysical Union Volume 32, Number 1 February 1951

MAJOR SHEAR FRACTURES OF ALASKA AND ADJACENT REGIONS

S. S. West

Abstract--Stream directions and shorelines in Alaska, Siberia, and Canada suggest the existence of three major sets of almost perpendicular pairs of shear fractures, which correspond to forces originating (1) in the Beaufort Sea, (2) in the bay of the Arctic Ocean near latitude 80° N, longitude 123° E, and (3) from a direction a few degrees east of north from Bering Strait. Available geologic evidence tentatively dates these fracture sets, respectively, as having been produced (1) between Lower and Upper Cretaceous, (2) between Upper Triassic and Jurassic, and (3) in the late Carboniferous or earlier. The first and last sets roughly fit the shear nets calculated by Vening Meinesz for shifts of the pole. Each of the three sets is associated with a distinct segment of the Aleutian Island arc, whose dimensions are here compared with those predicted by the overthrust theory of Gunn.

Published investigations of Alaskan geology have usually dealt with small portions of the Territory and given little attention to consideration of the general geologic history of the Arctic land masses. However, there exists in the literature and available charts and maps enough information to make possible a rough correlation of the structure of a wide area over a rather long period of geologic time. For this purpose we shall start with the Aleutian Islands which extend west from the Alaska Peninsula to longitude 171° E, and are paralleled on the south by an ocean deep whose bottom is lower than 4000 fm in many places and by a line of earthquake epicenters. The islands are volcanic along almost the whole length of the chain, and have been at least since Tertiary time. Aside from studies of volcanism, there are few published records of geologic work done in the Aleutians since the time of DALL [1896]. Only one paper [SHARP, 1946] has appeared in support of reports of occurrences of sedimentary rocks.

Seen on a small-scale map, the islands appear to form a continuously curving arc, and inferences concerning their origin are sometimes drawn from this arcuate shape. Examination of the large-scale charts of the UNITED STATES COAST AND GEODETIC SURVEY [1944] shows instead that they divide themselves into three almost linear groups, differing in orientation, depth of foredeep, and depth of the sea to the north. In addition, the line of separation between the eastern and central segments of the chain coincides on the north with the edge of the continental shelf, which runs north-northwest from Unalaska Island to the Pribilof Islands. The central and western segments join with distinctly different directions at about longitude 180°, along which meridian a shallow bank runs north for three degrees of latitude, with sea deeper than 2000 fm on both sides. (The Alaska Peninsula as far east as the Shumagin Islands is considered in the following discussion as part of the Aleutians.)

The greater part of the Bering Sea, between Alaska and Siberia, is shallow, the depth being of the order of 30 fm. Beyond a continental shelf of similar depth, the Arctic Ocean deepens rapidly to 1500 fm or more. North of Alaska, the 100-fm contour is as close to land as 70 mi, but it lies as far from the northern coast of Siberia as 450 mi.

For some years GUNN [1947] has been elaborating a theory of tectonics, by which he treated in the paper cited the quantitative aspects of juxtaposed ocean deeps, mountain chains and volcanic ranges. We shall find it instructive to examine the Aleutian Islands in the same way that he examined the west coast of Mexico. Gunn explains the existence of an oceanic trench or foredeep, with associated parallel bands of gravity-anomalies, mountains and volcanic activity, by postulating a failure by shear, such that the landward part of a horizontally compressed lithosphere over-rides the lower oceanic section. In the simplest case, shear failure might occur uniformly along a straight boundary of considerable length, as south of Java or west of Mexico, but the shape of the Aleutian chain is markedly different. Here there are two possibilities: (1) Shear was initiated by a force applied over a narrow segment of the lithosphere, so that failure occurred at a point and was propagated thence in both directions as the overthrust developed. (2) Other applications of force from different directions distorted the fault at later epochs.

Because the lithosphere at a depth of several miles has greater strength then the rocks at the

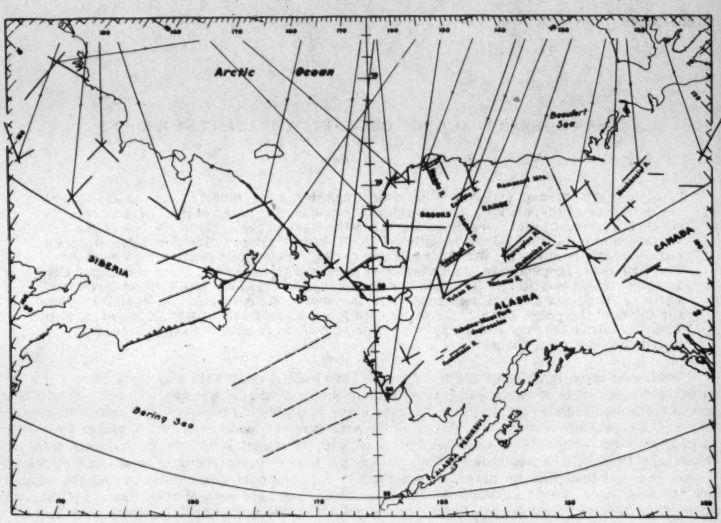


Fig. 1--Map of Alaska and adjacent regions, showing (in heavy lines) positions of representative pairs of shear fractures and (in lighter lines with arrows) direction of inferred force (Lambert conformal projection)

surface, the latter should fail first, secondary evidence of the application of a force then being observable in the presence of a set of paired shear-fractures en echelon over a wide area. At times these fractures will determine stream directions, and at other times they will encourage block faulting, so that one might expect to find them indicated by long straight segments of streams, begun or ended by abrupt bends, and by the relatively uneroded portions of shorelines. At least three such pairs of apparent fracture sets can be found on a map of Alaska, suggestive of stress in different epochs. Examples of each kind of pair are shown on the map of Figure 1 with some parallel fractures not obviously paired.

The geological history of Alaska seems to have been unusually favorable for the determination of stream courses by faults, and many more examples can be found than are shown on the map. An extended study of each stream might be worth while, though even the best maps available are not as accurate as might be wished. Moreover, the effects of erosion and local stratigraphy are magnified with the scale of the map. For the present it is sufficient to know the direction of the force within a few degrees of arc.

The examples of apparent concurrent fractures shown in Figure 1 determine three directions of thrust, if one assumes that the direction of force bisects the acute angle between shears. (Where the angle is near 90°, the uncertainty of measurement is often greater than the departure from a right angle, and other considerations must decide which angle is called "acute.") In one case, the angle is usually between 80° and 85°, and the direction varies from N20° E to N35° E. In the second case, the angle is sometimes as small as 70°, and the direction varies from N20° W in central Siberia to N45° W in northeastern Alaska. In the third case, the angle is almost 90° and the direction a few degrees east of north. The first and second directions are determined chiefly by streams, while the third depends upon shorelines and is therefore subject to greater error. It is interesting to note that the inferred force in the first case came from the direction of the Beaufort Sea, which is the nearest deep portion of the Arctic Ocean to the coast of Alaska, while the second force appears to have diverged from approximately the position of the bay of the Arctic Ocean which is centered near latitude 80° N, longitude 123° E.

One must remember, of course, that the angle between fractures is known only at the surface and that we are assuming the fractures to be approximately vertical. At least, the angles between shears are consistent with the indicated directions of applied force. Although directions of shearing stress are always perpendicular at a point, they converge to a smaller angle over a finite distance in the case of a load concentrated on a small portion of the boundary [FROCHT, 1948, p. 43, Fig. 2.10c]. Another interpretation has been given recently by VENING MEINESZ [1947]. The shear pattern which he calculated for a shift of the pole over 70° along the meridian of 90° E longitude corresponds rather closely to our third case, mentioned above. Moreover, his shear pattern for a further shift of the pole over an angle of 10° in longitude 0° is similar to our first case, in which the force appears to have come from the direction of the Beaufort Sea. The correspondence, however, is not exact, and the shear nets of Vening Meinesz show obtuse angles between shears where acute or right angles are inferred from topography.

Trends suggesting parallel fractures striking between N65° E and N75° E are found to be especially clear over a large part of the area under discussion. This approximate direction is characteristic of such river courses as (1) the lower Meade River, (2) the middle Colville River, (3) the Koyukuk River below Allakaket, (4) the Porcupine and Yukon Rivers from Old Crow to Stevens Village and from just below Tanana to Ruby, (5) the Chatanika River, (6) many segments of the Tanana River, (7) the Mackenzie River from longitude 131° W to 133° W, (8) three segments of the Kuskokwim River between longitude 156° W and 159° W, and (9) streams of the Takotna-Nixon Fork depression on the middle Kuskokwim River. In the last of these examples, the streams have trends of about N65° E (though the depression as a whole trends N50° E) and were believed by MERTIE [1936] to indicate "an extensive fault or zone of faulting." Two very large faults in the Alaska Railroad region have been described by CAPPS [1940], one in the eastern part of Mt. McKinley National Park with an average strike of N75° E, and one near Chickaloon with a strike of about N70° E. The eastern part of the Brooks Range has the same direction. The existence of nearly-perpendicular fractures is much less clearly indicated, so that a marked asymmetry is present.

Since the mountains of Alaska have almost all been formed by intrusion and extrusion of igneous material, it seems probable that their locations were determined by such shear faults, through which the underlying magma could escape. In many cases this molten material never reached the surface, but was only exposed as rock after erosion, so that one might expect to find elsewhere quite large masses of igneous rock still covered by flat-lying beds of Tertiary age or older. The ages of the intruded rocks, which can help to date the fractures, are known roughly. The western part of the Brooks Range appears to have been uplifted by basic intrusions possibly in late Mississippian time, but almost certainly earlier than Jurassic [SMITH and MERTIE, 1930, p. 261]. From a large exposure of intrusive granitic rock in the Romanzof Mountains near the head of the Canning River [SMITH, 1939, p. 90], and from pebbles of granite found in conglomerate on the Alatna River [SMITH and MERTIE, 1930, p. 264], it appears that the eastern part of the range was formed by the intrusion of granitic material which invaded Devonian and Carboniferous rocks but not Upper Cretaceous. The ages of igneous rocks in the Yukon Valley and farther south are not well enough known to assist the dating.

Although the lithosphere carries most of a thrust at great depth, surface rocks will be deformed by the stress (more so when they are rigid and cannot compress), and when the lithosphere is deformed as a whole the surface deformation must be still more severe. Now in northern Alaska the Mississippian and overlying Upper Triassic rocks are very strongly folded together, and older rocks also are intensely deformed, broken, and metamorphosed [SMITH and MERTIE, 1930, pp. 173-178]. Smith and Mertie further noted [pp. 202-205] that the Lower Cretaceous rocks are extensively folded and have been "affected by enormous diastrophic movements and stresses." They are overlain unconformably by the Upper Cretaceous in many places. Combining this evidence with that of the preceding paragraph, one can deduce tentatively that the faults with one axis striking parallel to the western part of the Brooks Range resulted from a stress applied between Upper Triassic and Jurassic times, and those with one axis striking parallel to the eastern part of the Brooks Range from another stress applied between Lower and Upper Cretaceous times. More accurate dating must await the publication of further geological information.

The evidence cited suggests the following geologic history: One assumes first that there existed in early Paleozoic time, a land mass where the Arctic Ocean now is. At some time probably in the late Carboniferous, this land mass became unstable and began to subside, thrusting southward and initiating an overthrust shear fault in the Aleutian region. Simultaneously horizontal shear faults split the intervening rocks into blocks whose later relative vertical motions produced the present coasts and continental shelves. Subsidence of a large block north of Siberia between Upper Triassic and Jurassic times increased the overthrust toward the southeast and made it asymmetrical.

Table 1--Dimensions of the Aleutian Island arc

Depths and heights[a]	Eastern segment	Central segment	Western segment
Length of deep in longitude	158° W-165° W	165° W-180°	180°-171° E
Average depth of bottom of foredeep[b]	6.85	7.15	7.30
Maximum depth of foredeep	7.25	7.40	7.70
Depth of ocean south of foredeep	4.73	4.90	5.20
Depth of sea north of islands	0.08	3.50	3.95
Depth of continental shelf	0.09	0.11	indefinite
Distance from bottom of foredeep to edge of continental shelf	95	130	indefinite
Distance from bottom of foredeep to maximum height of volcanoes	225	160	153
Maximum height of volcanoes above sea level	2.87	2.10	1.22
Approximate average height of volcanoes	0.90	1.10	0.60
Direction normal to long axis of foredeep	N20° W	N8° W	N20° E
Approximate slope of north side of foredeep	4.3°	2.9°	3.7°
Depth of bottom of foredeep below undisturbed ocean bottom	2.23	2.30	2.23
Maximum height of volcanoes above undisturbed ocean bottom	7.60	7.00	6.40
Average height of volcanoes above undisturbed ocean bottom	5.63	6.00	5.80
Island segment of arc	Shumagin Islands to east end of Unalaska Island	Unalaska Island to Amchitka Pass	Amchitka Island to Stalemate Bank (west of Attu Island)

[a]All distances are in kilometers.
[b]By "bottom of foredeep" is meant place of greatest depth of water in cross-section normal to long axis.

Finally, subsidence of a third block between Lower and Upper Cretaceous times to form the Beaufort Sea created a thrust toward the southwest and completed the arcuate shape of the fault system. The northeasterly striking shear faults from this latest movement must have been the most active of all, for they appear to have determined a large part of Alaskan Topography. Alternatively, one might adopt the hypothesis of VENING MEINESZ [1947], in which case the subsidence is no longer a primary phenomenon.

The important dimensions of the Aleutian Islands are listed in Table 1, as determined from the data of the UNITED STATES COAST AND GEODETIC SURVEY [1944, 1948]. All distances are given in kilometers. We can now compare the measured values with theoretical predictions.

The theory of GUNN [1937, 1947] represents, as an elastically supported beam, a section of a homogeneous elastic lithosphere having unit width and long axis normal to the greatest dimension of the deep. Orienting the y-axis vertically, the x-axis along the beam, and the z-axis parallel to the deep, one obtains the differential equation

$$EI\, d^4y/dx^4 + ST\, d^2y/dx^2 + (d_o - d)gy = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

in which

T = thickness of section
E = Young's modulus of elasticity
I = section moment of inertia per unit width = $T^3/12$
S = horizontal compressional stress along x-axis
d_o = density of supporting magma
d = density of material deposited on top because of deflection
g = acceleration due to gravity

For a complete discussion of this equation, one may refer to the papers cited or to an advanced engineering text. The point of chief interest is that two types of solutions exist according as the roots of the auxiliary equation are real or complex, or as the stress S is less or greater than a

critical value $[(d_0 - d)gET/3]^{1/2}$. In the first case, the solution is quasi-periodic and has the form

$$y = Pe^{-ax} \sin bx + Qe^{-ax} \cos bx \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

while in the second it is periodic and of the form

$$y = B \cos (kx + c) \quad \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Eq. (2) represents the uplift of the end of the beam by over-riding at a shear fault, or the downthrust of the seaward portion to form the foredeep. When S is small compared to its critical value (about 7×10^{10} dynes/cm^2 for $E = 1.1 \times 10^{12}$ dynes/cm^2 and $T = 5 \times 10^6$ cm), we have to a good approximation

$$a = b = q \quad \ldots\ldots\ldots\ldots\ldots\ldots (4)$$

where q is defined by

$$q^4 = 3(d_0 - d)g/ET^3 \quad \ldots\ldots\ldots\ldots\ldots\ldots (5)$$

GUNN [1943] has found q to be about 8.4×10^{-8} cm^{-1} from measurements of gravity. It can also be shown [GUNN, 1947] that the maximum fiber stress, where volcanoes are most likely, will occur at a distance from the surface trace of the fault approximately equal to $(\pi/4q + 0.5T \cot \phi)$, where ϕ is the angle between shear plane and horizontal compressive force S. When one assumes $\phi = 45°$ and takes for q and T the values given above, this distance is 118 km.

The upward or downward deformation of the axis of a sheared beam is given [GUNN, 1947] for small value of S by

$$y = [q\, e^{-qx} \cos qx \sin 2\phi]ST/(d_0 - d)g \quad \ldots\ldots\ldots\ldots\ldots\ldots (6)$$

On the other hand, a stress which exceeds the critical value will throw the crust into a wave-like deformation according to (3), the distance λ between crests being

$$\lambda = 2\pi(ST/dg)^{1/2} \quad \ldots\ldots\ldots\ldots\ldots\ldots (7)$$

Comparing the theory for the beam sheared at small stress with the data of Table 1, one finds that for depth of foredeep below the undisturbed ocean bottom there is satisfactory agreement. Allowing for deposition of sediments according to the measured slopes, one can compute the original depths of the eastern, central, and western foredeeps to be 2.9, 3.8, and 3.1 km, respectively, which fall within the predicted range of 2.0 to 4.0 km [GUNN, 1947]. The predicted 175 km from greatest depth of water to volcanoes is also reasonably close to the measured 225, 160, and 153 km of the three segments of the island chain.

There are, however, the following interesting discrepancies: (1) The distance from greatest depth of water to volcanoes is not the same (even allowing for sediments) from one segment to another, although it is roughly constant along a given segment. (2) A coastal mountain range exists only in the eastern segment, and there [MURRAY, 1945, 1946] it is submerged and extremely irregular. (3) A basin ("backdeep" or "geosynclinal sea") exists behind the central segment and behind the western segment, as is the case for many other island chains with foredeeps. This basin is much deeper than permitted by the exponential factor of (6), which gives it a depth less than four per cent that of the foredeep.

Inability to predict the existence and magnitude of the backdeep is the most serious deficiency of the simple sheared-beam theory, for such a basin behind the volcanoes is more the rule than the exception. However, agreement is so good in other respects that perhaps only minor refinement is needed.

The directions normal to the eastern, central, and western segments of the Aleutian Islands are N20° W, N8° W, and N20° E, respectively, and lines drawn in those directions from the centers of the segments pass through the portions of the Arctic Ocean previously mentioned. It seems very probable, therefore, that the thrusts inferred from river courses farther north were also those which produced the Aleutian deep.

In conclusion, I express my appreciation for the assistance of the Geophysical Institute of the University of Alaska in providing facilities for this investigation.

References

CAPPS, S. R., Geology of the Alaska Railroad region, U. S. Geol. Surv. Bull. 907, 1940.
DALL, W. H., Report on coal and lignite of Alaska, U. S. Geol. Surv., 17th Ann. Rep., pt. 1, 1896.
FROCHT, M. M., Photoelasticity, v. 2, John Wiley and Sons, Inc., New York, 1948.
GUNN, ROSS, A quantitative study of mountain building on an unsymmetrical Earth, J. Franklin Inst., v. 224, pp. 19-53, 1937.
GUNN, ROSS, A quantitative evaluation of the influence of the lithosphere on the anomalies of gravity, J. Franklin Inst., v. 236, pp. 47-65, 1943.
GUNN, ROSS, Quantitative aspects of juxtaposed ocean deeps, mountain chains, and volcanic ranges, Geophys., v. 12, pp. 238-255, 1947.
MERTIE, J. B., JR., Mineral deposits of the Ruby-Kuskokwim region, Alaska, U. S. Geol. Surv. Bull. 864-C, 1936.
MURRAY, H. W., Profiles of the Aleutian trench, Bull. Geol. Soc. Amer., v. 56, pp. 757-782, 1945.
MURRAY, H. W., Submarine relief of the Aleutian trench, Trans. Amer. Geophys. Union, v. 27, pp. 871-875, 1946.
SHARP, R. P., Note on the geology of Agattu, an Aleutian island, J. Geol., v. 54, pp. 193-199, 1946.
SMITH, P. S., Areal geology of Alaska, U. S. Geol. Surv. Prof. Pap. 192, 1939.
SMITH, P. S., and J. B. MERTIE, JR., Geology and mineral resources of northwestern Alaska, U. S. Geol. Surv. Bull. 815, 1930.
UNITED STATES COAST AND GEODETIC SURVEY, Chart No. 8802, Alaska Peninsula and Aleutian Islands to Seguam Pass, 17th ed., 1944.
UNITED STATES COAST AND GEODETIC SURVEY, Chart No. 9102, Aleutian Islands-Amukta Island to Attu Island, 10th ed., 1948.
UNITED STATES GEOLOGICAL SURVEY, Alaska Map E, 1946.
VENING MEINESZ, F. A., Shear patterns of the Earth's crust, Trans. Amer. Geophys. Union, v. 28, pp. 1-61, 1947.

Geophysical Institute,
University of Alaska,
College, Alaska

(Manuscript received March 22, 1950, and, as revised, June 19, 1950; presented at the Thirty-First Annual Meeting, Washington, D. C., May 2, 1950; open for formal discussion until July 1, 1951.)

Transactions, American Geophysical Union Volume 32, Number 1 February 1951

ON THE ORIGIN OF THE CAROLINA BAYS

William Schriever

Abstract--A critical reconsideration of all important theories concerning the origin of the Carolina Bays led to a modified meteorite theory of origin, and to the conclusions: (1) Johnson's theory of "complex origin" is quite untenable; (2) a modified meteorite theory of origin can meet all of Johnson's 29 requirements; (3) such a meteorite theory of origin has not yet been shown to be untenable; and (4) the modified meteorite theory of origin is the least unsatisfactory of all the theories which have been published thus far.

Introduction--It has now been 17 yr since the publication by the writer and his colleague, MELTON [and SCHRIEVER, 1933] of their paper which brought to the attention of the scientific world the problem concerning the origin of the Carolina Bays. JOHNSON [1942] concluded his book with these statements: "The Carolina Bays are without doubt one of the most remarkable geomorphic features on the surface of the Earth. They share with submarine canyons the distinction of being among the most difficult of earth forms to explain. They are literally innumerable, and one investigator can see relatively few of them. A large field of study thus remains open, and new and pertinent facts doubtless remain to be discovered."

During these 17 yr numerous investigators have studied these bays and numerous papers concerning them have appeared in scientific journals. Johnson's book reviews all the pertinent information published prior to 1942 concerning the Carolina Bays. In addition it sets forth in great detail his "Hypothesis of complex origin." In it Johnson also discusses in great detail the meteorite theory of origin of the bays, which was proposed by MELTON and SCHRIEVER [1933], together with certain other theories of origin proposed by others. As a result of his valuable studies, Johnson concludes that all theories of origin, except that of "complex origin," "seem quite incapable of accounting for the vast array of facts which must be explained by any acceptable hypothesis."

Johnson's 29 requirements of a satisfactory hypothesis--JOHNSON [1942, Chap. 9 and 10] states 29 "Requirements of a satisfactory hypothesis" and discusses these 29 requirements and the "Competence of the hypothesis of complex origin."

Let us examine a meteorite hypothesis of origin of the bays in the light of the 29 requirements proposed by Johnson, without questioning their validity. Let us assume, for the sake of argument, that a swarm of meteorites struck the coastal plain while it was yet under the shallow sea, that the action of the waves filled in the craters, and that the plain then rose above the water. After emergence of the bays there could well have been some compaction of the loose fills. In addition, the strata would have been penetrated and cracked to a depth of hundreds of feet by the meteorites. Rain water, and perhaps shallow ground water, could have dissolved some of the material in, around, and beneath these former craters, thus permitting the fill in each bay to settle until the depression would hold water as many of the bays do even at the present time.

Let us now consider Johnson's requirements. Of these only ten need individual attention. The other 19 requirements can be disposed of with a single comment which applies to each, namely, Johnson's discussion could apply equally well to meteorite craters once they are formed.

These 19 requirements are (Johnson's designation): (A) Many of the craters are of remarkably perfect oval outline. (C) Many craters are highly irregular in outline. (G) Craters vary in size: some are a few hundred feet, many one or two miles, and some three or four miles in longest direction. (J) Both large and small craters show considerable variation in degree of ellipticity. (K) Oval craters normally are not true ellipses or true ovoid forms, but show systematic bilateral asymmetry, the northeastern sides usually being more sharply curved than the southwestern. (N) Many craters are bordered by rims of sand. (O) Many craters similar in all other respects have no rims associated with them. (P) The rims when present rarely completely surround a crater; incomplete rims are sometimes erratically distributed but normally are highest and broadest about the southeastern quadrants of the depressions. (Q) Multiple rims, nearly but not quite

concentric, and from two or three up to six or eight and possibly more in number, occur about some craters. (R) Such multiple rims tend to be best developed and farthest apart toward the southeastern ends of oval and ovoid craters, converging or merging or disappearing toward the northwestern ends. In some cases the multiple rims are chiefly confined to the eastern sides rather than the southeastern ends of the craters. (S) A wide space sometimes intervenes between an outer rim or series of rims and an inner rim or series within the same crater; this distribution pattern may be repeated in adjacent craters. (T) The rims are of relatively insignificant size, the volume of material contained in them being but a small fraction of the material removed to form the craters. (U) The convergence of multiple rims of the same crater and the junction of contiguous rims of adjacent craters do not give rise to combined rims of unusually large size. On the contrary, such combined rims may be unusually small and may locally disappear. (V) There is no systematic relation between the size of the bays and the size of their bordering rims. Large bays may have small rims or none and small bays may have large rims. (W) Many rims are relatively flat-topped or broadly rounded in cross section, frequently with steeper slopes inward toward the crater and outward toward the adjacent plain. (X) The composition of the rims is remarkably uniform, the material consisting for the most part of clean, fairly coarse white or buff quartz sand. (Y) Material composing the Coastal Plain in which the craters are excavated is often strikingly dissimilar to the material composing the rims. (BB) Many craters have channels draining into or out of them. (CC) These channels frequently cut across rims bordering the craters.

The ten requirements which need individual consideration will be discussed next.

(B) "In some localities the ovals are prevailingly elliptical, in others distinctly ovoid or egg-shaped." A careful eximination of Johnson's Figure 30 [p. 173] (Index mosaic of aerial photographs covering part of Barnwell Co., S. C.) suggests an explanation for Johnson's so-called ovoid craters; evidently they were elliptical craters which have been modified by being filled with sand along their east shores. The evidence also indicates that the axes of the original ellipses extend very approximately along NW-SE lines. Unfortunately, in the area shown in this mosaic, cultivated lands completely surround the bays so that the shapes of some of the bays, as revealed by the mosaic, undoubtedly have been much modified by the fields. The clearest illustration of sand-filling on this mosaic is that shown by the large bay a little to the S and W of the center of the picture. Figure 1 illustrates how different degrees of filling of an elliptical bay change the direction of its axis as recorded by Johnson. Thus various degrees of sand filling of different bays will account for the wide range of values of axis-direction stated by Johnson (see E and F below). This sand-filled condition appears to be especially well illustrated by the large bay near the lower center of Johnson's Figure 36 [p. 184], and also by the large bay in Figure 34 [p. 182]. Although the mosaic maps do not reveal the original ellipse for every ovoid bay, it is quite reasonable to suggest that all the ovoid bays of the Carolina type were originally elliptical and had major axes along NW-SE lines. Usually only large bays reveal the degree of sand filling at the present time.

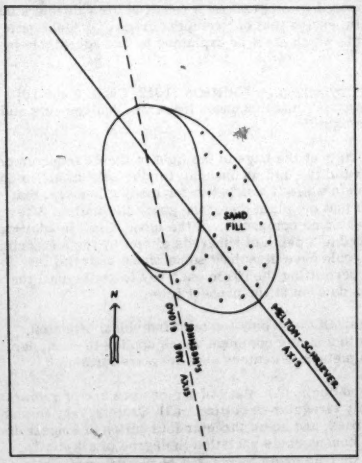


Fig. 1--Illustration showing how a sand fill in a typical elliptical Carolina Bay has produced an ovoid bay whose apparent major axis extends south of southeast; different degrees of filling have produced different directions of the apparent major axes of a number of bays

(D) "All gradations in form exist, from craters of the most regular outline to those highly irregular." Johnson's discussion is really covered by (C) and would apply equally well to meteorite craters. It must also be remembered that, in the general region of bay occurrence, depressions of various kinds, such as typical sinkholes, exist. These appear to be in no way connected with the bays and need not be explained by the theory which may be appropriate for the bays.

(E) "Oval craters have axial trends almost always directed between south and east, most of

them ranging between S10° E and S55° E." During the many centuries that the bays have existed, the windblown sand and the waves of these crater-lakes undoubtedly have modified the shapes of the bays. Therefore, the axes of the bays at the present time may deviate more from one another than they once did. The directions of the axes of the typical well-developed single bays deviate from one another very much less than the scatter from 10° to 55° stated by Johnson. The latter part of Johnson's discussion concerning modification by NW winds could apply equally well to meteorite craters. The causes for the various orientations of the axes of bays is explained in (B) above; this explanation is not in accord with that of Johnson [bottom p. 185 and p. 183]. However Johnson's suggestion on page 206 may apply.

(F) "There are wide departures from the prevailing direction: elliptical craters are most consistent in trend, with axes directed more or less nearly southeast; ovoid craters are most variable in trend, but as a rule have axial directions more nearly southward, their narrow ends pointing in this direction." An explanation has been suggested under (B) and (E) above.

(H) "The craters are remarkably shallow in comparison with their great areal extent." There appears to be nothing in Johnson's discussion which would rule out the meteorite hypothesis; much of what he says would apply to meteorite craters.

(I) "The craters descend below the level of the surrounding plain and below the bases of their bordering rims, as if they were depressions caused by removal of part of the Coastal Plain material." In no way does this appear to rule out the meteorite hypothesis.

(L) "Craters sometimes occur in systematic groups with a distinct group pattern apparently determined by some pre-existing topography or strucutre." Such alignments occur probably no more frequently than might be expected in a "random" shower of meteorites. If the beach ridges developed later as suggested by the writer then one would expect them to be influenced by the pre-existing bays. This is discussed again in the fourth paragraph of the next section on "Objections."

(M) "Oval craters, while abundant on parts of the Coastal Plain, are apparently absent from the Piedmont and other Appalachian provinces." Melton and the writer in their first paper suggested that if such a cluster of meteorites were spherical, and if the Carolina Coastal Plain were struck by the center of such a cluster, then craters would be expected in the Piedmont and out in the ocean. But there is no compelling reason why the cluster must be spherical. The meteorites could have fallen only along the coast, or only along the coast and out in the ocean, and none in the Piedmont.

(Z) "Bedrock fragments of Coastal Plain sediments are not found in the rims." If the bays were developed from meteorite craters starting beneath the sea, as the writer has suggested above, then, bedrock fragments could very well be absent at the present surface of the Coastal Plain.

(AA) "Coastal Plain sediments normally remain undisturbed in a horizontal position below the sandy rims and in the crater walls. Occasionally there is a slight indication of slumping inward toward the craters but no uplifting of beds causing them to dip outward away from the craters." According to Johnson's explanation the craters have been enlarged by wave action, the edges of the soft surface material having slumped into the crater-lakes. In such a case the upturned edges of the original meteorite craters would have been worn away in the many centuries of their existence, and could even exhibit the slumping at the edges stated by Johnson. Thus Johnson's discussion could apply equally well to meteorite craters.

Thus it appears that none of Johnson's 29 "Requirements of a satisfactory hypothesis" for the origin of the Carolina Bays has made a meteorite hypothesis of origin untenable. Of course, this in no way proves that a meteorite hypothesis of origin is correct; it merely shows that such a hypothesis can meet all the requirements which Johnson required of his hypothesis of complex origin.

Objections to the meteorite hypothesis of origin--In Chapters 5 to 8 inclusive of his book, Johnxon has given a most detailed discussion of the Meteorite hypothesis of origin of the Carolina Bays; he devoted 100 pages--nearly one-third of his book--to this discussion. His objections to the meteorite hypothesis merit consideration here.

In his first objection [page 35] to the meteorite theory of origin he contends that, "There seems to be no escape from the conclusion that had oval basins and sandy rims existed in the Myrtle Beach area prior to construction of the beach ridges, the oval forms would not merely have been slightly modified or partially obscured; they would have been annihilated" (while coming out of the sea and

passing through the shore building processes). Whether or not this would be the case would depend on how fast the relative sea level changed.

For the sake of argument, let us suppose that the sand rims were "annihilated" as Johnson assumes. As has already been explained in this paper, after the obliterated craters emerged from the sea they could well have formed lakes. Then the same winds and waves that might build rims in Johnson's "Hypothesis of complex origin," would build rims for the meteorite scars.

On page 58 Johnson states, "We must conclude that the beach ridges, the parallel depressions between pairs of beach ridges, and the irregular depressions between different areas of beach ridges are fairly early features of this old shore zone; and that the ovals, developing later, were influenced by pre-existing forms or structures of the region." It is proper to point out that it is just as logical to conclude that the bays were there first and that the locations of the beach ridges were influenced by the pre-existing bays with their rims. In fact, on page 54 Johnson states, "While the vague and confused assemblage of imperfect ridges and swales and equally imperfect basins and rims are reasonably open to the interpretation given by Melton and Schriever (that the ovals and rims were formed first and later obscured by the process of beach ridge building), they are equally open to the opposite interpretation." In the writer's opinion, Johnson has presented no evidence which would compel one to conclude that the craters were formed later than the beach ridges.

On pages 64-69, Johnson concludes that the elliptical form of the craters cannot be due to the impact of large meteorites at oblique angles. He states, "If the angle of impact be sufficiently high for the mass to enter the ground, even a large meteorite does not produce a prominent crater but a pit with diameter not notably greater than that of the meteorite itself." He next argues that such large meteorites when striking our Earth with high velocities would explode and therefore produce round craters, and not elliptical ones. Let us examine the largest confirmed meteorite crater, namely Meteor Crater near Winslow, Arizona. This crater is over 4000 ft in diameter; it is slightly elliptical, the major axis being 250 ft longer than the minor axis. This crater was described in detail by JAKOSKY, WILSON, and DALY [1932]. In their work these authors examined Meteor Crater, Arizona, very carefully by both geological and geophysical methods, the latter including both magnetic and electrical methods of prospecting. Their paper shows sectional views of the crater along both the major and the minor axes of the ellipse. The section along the major axis shows that the meteorite struck at an angle and that its remains are now located inside the rim well beyond the center of the crater on the major axis.

JAKOSKY [1932], further reported the results of drilling in Meteor Crater. He states, "The electrical survey located the meteorite in the southwestern part of the crater, and indicated it to consist of a shallow fragmentized zone, surrounding a more concentrated main mass occurring at an effective depth of 700 ft below the present crater floor." This was confirmed by the magnetic survey.

He continues, "The first hole, placed in the center of the favorable area indicated by the geophysical survey, ran into the zone containing meteoric fragments at a depth of 414 ft. At 675 ft further progress was halted as the drill became lodged in the upper part of the more concentrated meteoric zone. The existence of the meteoric material was further proved by analyses which showed the presence of nickel. The second drill hole, as far as it has been carried out, revealed similar conditions to the first."

It seems reasonable that a huge meteorite, perhaps even hundreds of feet in diameter, when it struck the Earth, would make a "splash" in the Earth similar in appearance to the splash made by a pebble when it is dropped into thin mud. That such a meteorite would "explode" is certainly contrary to the facts found at Meteor Crater, Arizona, by geological methods, geophysical methods, and drilling. That steam, produced by the heat of impact, blew out some material is entirely possible, but the meteorite, as such, did not explode. These findings also indicate that the diameter of this meteorite was very much less than the diameter of the crater which it produced.

Thus Johnson's statements concerning impacts of meteorites are contrary to the facts found in connection with the Meteor Crater, Arizona. This meteorite produced an elliptical crater; it did not explode; and its diameter was much smaller than the diameter of the crater which it produced.

On page 72 Johnson states, "The force of the meteorite hypothesis as an explanation for axial direction is greatly weakened by the fact that the close parallelism of axial direction upon which this hypothesis was predicated does not actually exist." Since the lack of parallelism of the bays

as observed by Johnson was caused by his method of drawing axes through the "ovoid" bays, his statement is not convincing. In the discussion under "Requirement B" presented earlier in this paper, an explanation is given which indicates that this remarkable parallelism of the major axes of the original bays very probably does exist.

Johnson, on page 97, objects to the meteorite origin of the Carolina Bays, because many of these bays are larger than any other known meteorite scar. As far as the writer is aware there is no reason to assume an upper limit to the possible sizes of meteorites or their resulting scars.

In Chapter 8 Johnson discusses the published data and conclusions arrived at by geophysical prospecting the area of the Carolina Bays with magnetometers. His criticisms may be stated briefly. First, since magnetic prospecting did not reveal a magnetic "high" on the axis and southeast of each bay, the bays cannot be of meteorite origin. Second, since magnetic "highs" do occur over the area at points where they are apparently not associated with bays, all magnetic highs must be due to features other than meteorites. And third, Johnson makes much of the fact that the magnetic "highs" are not found on extensions of the axes of the bays, where, according to him they should be found if they were caused by meteorites, but are found off to one side of the axes.

Let us first consider the third point. Let us assume with Johnson that a meteorite which had produced a crater would come to rest approximately on an extension of the axis of the crater and southeast of it. The magnetic "high" then would not occur directly above that meteorite, but somewhat magnetically south of that meteorite and therefore off the axis of the crater. This shift of the "high" to the magnetic south would exist because the direction of the Earth's magnetic field dips at an angle from the horizontal. This shift may be verified in any treatise on magnetic prospecting.

In considering the first point above, one must remember that meteorites are of three general varieties: (a) nickel-iron, (b) stony, and (c) those made of a mixture of nickel-iron and stone. Only meteorites having a high iron content would cause appreciable magnetic "highs." In addition, it is known that the majority of the meteorites which fall on the Earth are stony. Thus, a swarm of meteorites such as the meteorite theory requires for the production of the Carolina Bays, could all be stony, or all nickel-iron, or all could be mixtures, or the swarm could have contained meteorites of any two or all three of these varieties. Therefore, it should not be at all astonishing if some bays failed to exhibit magnetic "highs" at the appropriate places. In fact, it would be entirely possible to have no magnetic "highs" caused by meteorites even though the bays were produced by them. On the other hand, if a magnetic "high" were found approximately southeast of each bay, this would be considered as good support for the meteorite theory of origin.

In regard to the second criticism, it was not unexpected that magnetic "highs" would be observed on the Carolina Coastal Plain and that these appeared not to be associated with the bays. But the existence of these magnetic "highs" is no argument either for or against the hypothesis of meteorite origin of the Carolina Bays. In fact, even some of these extraneous magnetic "highs" could be caused by meteorites. It is known that large meteorites are often accompanied by small ones. Thus, if the huge crater-producing meteorites which may have struck the Carolinas were accompanied by relatively small nickel-iron meteorites (sizes of only a few hundred tons each), the latter would not have produced deep craters and would be quite near the surface. Such chunks of nickel-iron near the surface would produce large concentrated magnetic anomalies. Groups of such chunks of nickel-iron would cause a very complicated magnetic picture, which would show no relation to the existing bays.

Johnson states other objections to the meteorite theory of origin of the Carolina Bays, but these have been answered in the writer's discussion (earlier in this paper) of his 29 "Requirements of a satisfactory hypothesis." Thus it appears that a meteorite theory of the origin of the Carolina Bays is capable of meeting all of the objections to it, which thus far have been raised.

Hypothesis of Complex Origin--Next let us examine Johnson's Hypothesis of Complex Origin, "the artesian-solution-lacrustrine-aeolian hypothesis." In it he "supposes that artesian springs, rising through moving ground water and operating in part by solution, produced broad shallow basins occupied by lakes, about the margins of which beach ridges were formed by wave action and dune ridges by wind action." (Underscore is his.)

On page 154 Johnson states, "It appears at once that the regional slope of the Coastal Plain concides fairly closely with the axial trends of many of the elongated craters. But all efforts to find a causal connection between crater form and orientation on the one hand, and regional slope of the Coastal Plain on the other, encounter an insuperable difficulty. . . . . Their (the craters') elongation is demonstrably independent of the direction of inclination of the immediate surfaces

in which the basins are excavated."

Johnson then proceeds with the discussion of his theory of origin and development of the bays. It involves no less than 15 explicitly stated assumptions, together with a number of implicit assumptions. The validity of certain of his assumptions, explicit and implicit, appears to be open to question.

After due allowance is made for sand filling in along the eastern shores of the bays in some areas, notably in the southern part of the region occupied by typical bays, it is observed that the long axes of the bays are remarkably nearly parallel, the axes extending almost due SE, which is Johnson's assumed direction of regional dip of the underlying strata. The region in which bays occur extends a distance of some 400 mi in the direction of his assumed strike of these strata (NE-SW), and covers an area of some 35,000 sq mi. The theory based on the Hypothesis of Complex Origin requires that the dip of the strata over this entire area be remarkably constant and directed to the SE. The theory also requires that the characteristics of the various strata (as regards porosity, solubility, supply of artesian water, and other factors) be remarkably constant over the entire area of 35,000 sq mi. Perhaps such uniformity over such a large area is entirely possible but it certainly is very uncommon.

It appears that the Carolina Coastal Plain is not in any way a unique area, geologically speaking, if one ignores the features known as the Carolina Bays. Since similar coastal plains exist at many places over the Earth, is it not remarkable that on not even one other coastal plain have there developed oval craters like the Carolina Bays? During the last 17 yr the Carolina Bays have been given much publicity both in scientific journals and in popular magazines. Yet in all that time, as far as the writer is aware, not a single example of a group of typical Carolina-type oval depressions has been reported to exist in any other coastal plain region. It is evident that, either the Carolina Coastal Plain must be unique in certain important, but unknown, respects, or the origin of the Carolina Bays must have been due to an unique agent.

On page 162 Johnson states, "In a coastal plain like that of South Carolina and adjacent states it is not easy to determine the dip of the formations over different areas. The beds are so nearly flat that dips are usually imperceptible." And on page 163, Johnson writes, "Cooke reports by letter that this structure brings the Peedee formation almost to the surface at Wilmington, N. C., and along the Wacamaw River in northeastern South Carolina, whereas at Charleston the top of the same formation lies 500 ft below sea level."

A 140-mi line joining Wilmington and Charleston lies almost exactly NE-SW, namely along the strike of the strata required by Johnson's theory. Thus the Peedee formation has a component of dip of 3 1/2 ft per mi along this line. Actually the dip along this line must be more because NE South Carolina is only 100 mi from Charleston. Therefore if Cooke's statement is correct, the direction of maximum dip cannot possibly be almost exactly SE as is required for Johnson's theory of origin of the bays. In fact, the dip could be anywhere from much south of SE to much west of South. If the strata of the Carolina Coastal Plain do not have their direction of maximum dip almost perfectly to the SE, but more nearly south (or possibly even SW), as is suggested in Cooke's letter to Johnson (and referred to in preceding paragraph), then Johnson's theory of complex origin is rendered completely untenable and must be abandoned.

A confirmatory statement was supplied by C. Wythe Cooke of the U. S. Geological Survey, who replied to the writer's inquiry in January 1947 as follows: "I have published nothing specifically dealing with the dips of geologic formations in the Carolinas, though some information about dips can be inferred from the text and map of my report on the 'Geology of the Coastal Plain of South Carolina' (U. S. G. S. Bull. 867, 1936). A deep well at Charleston reported on by STEPHENSON [1915] at a depth of about 500 ft seems to have entered the Peedee formation, which crops out below tide at Myrtle Beach, 90 mi northeast. The dip at Charleston is probably southward." According to this information the average component of dip to the SW is 5.5 ft per mi. If the direction of maximum dip is south, it therefore must be 7.7 ft per mi on the average.

On the other hand if Johnson's statement is correct, namely, that the "beds are so flat that dips are usually imperceptible," then he has made his own theory untenable because his theory requires ground water to flow SE with sufficient vigor to cause the sands in a bay to become "quick" at its NW end and to be packed on its SE end. With such "imperceptible" dip the ground water flow would also be imperceptible and could not possibly produce all the effects he has required of it. In fact it is doubtful if any moderate dips could cause ground water flow of sufficient intensity to produce the effects Johnson has asked of it.

On pages 190 and 191, Johnson writes, "We should picture vast stretches of the Coastal Plain having the surface dotted with literally countless springs . . . . . , and all boiling or fountaining in greater or less degree due to the artesian pressure of water entering the sediments farther up the slope. . . . . Some sinkholes resulted directly from the solvent action of descending local rain water, others may have resulted from the caving in of underground channels and caverns in the soluble beds, while still others were developed by waters upwelling to the surface. The resulting "sinks" served in part as intakes for descending surface waters and in part as exits for uprising artesion waters depending on local conditions. These same openings might serve first one purpose, then the other, as changes in ground water level, underground circulation, and other local conditions occurred."

If the strata of the Coastal Plain had only "imperceptible dip" as Johnson states, then different parts of the Plain would all be nearly at the same level and the flow in at one "sink" and out at another would be an impossibility; his required flow of ground water could not possibly result for it would violate the law of conservation of energy.

Johnson appreciated the weakness of his own theory of complex origin when on page 179 he wrote: "At present, the number of artesian springs observed still fountaining in the craters, the number of lake basins known to be incompletely filled with peat bogs, and the number of basins for which we have depth measurements is in each case extremely small--far too small in comparison with the enormous number of existing craters to constitute a trustworthy demonstration of the validity of any hypothesis."

Since the dips of the strata of the Carolina Coastal Plain are either in the wrong direction, or much too gentle, or both, to permit the formation of the oval craters in the manner suggested by Johnson's "Hypothesis of complex origin," this hypothesis must be considered as quite untenable.

Hypothesis of segmented lagoons and crescent-shaped keys--A theory attributing the origin of the Carolina Bays to segmented lagoons and crescent-shaped keys was presented by COOKE [1934, 1940, 1943, 1945]. The reply by MELTON [1934] published as a supplement to Cooke's paper, explains why this theory is untenable. This theory was also discussed at length by Johnson (pp. 36-44); Johnson also concluded that the theory is untenable.

Lakes made elliptical by gyroscopic action--COOKE [1943] has also presented a theory to account for the elliptical shape of lakes and the orientation of their major axes in a due NW-SE direction in the northern hemisphere. In his development he assumes that the water in the lake is made to rotate about the center of the lake by wind action, and that the whole body of water of the lake then acts as if it were a large slow-spinning gyroscope located on our spinning Earth.

Even if it be granted that the body of water in the lake were rotating about the center of the lake, would that body of water, as a whole, exhibit gyroscopic action as Cooke has assumed? The answer must be negative, because dynamics requires that the spinning body of water be a rigid body, and a body of liquid water certainly is not a rigid body. Since this body of water is not a rigid body the dynamics of the gyroscope cannot be applied ot it. Consequently Cooke's conclusions cannot be drawn.

There is a well-known principle of dynamics which applies to each particle of water as it moves over the surface of our spinning Earth. In the Northern Hemisphere such a moving particle would be acted on by a force [HUMPHREY, 1940, p. 116] which would cause it to "deflect to the right" regardless of the geographic direction of its motion. In the Northern Hemisphere this action would tend to cause the water in a rotating lake to pile up in the middle of the lake if the rotation were clockwise (viewed from above) or to pile up near the edge of the lake if the rotation were counter-clockwise. For the low velocities which such lake water would have the effects would be exceedingly small. Even if they were large they could not bring about the formation of an elliptical bay, since for the same speed this force per unit mass of water would be the same regardless of the geographical direction of flow of the water.

The fish-bed hypothesis--A biological explanation of the origin of the Carolina Bays has been proposed by GRANT [1945]. A biological explanation requires a biological consideration. GUDGER [1946] wrote, "I spent ten summers at the Fisheries Laboratory at Beaufort, North Carolina, and seined all over the sounds round about. I know the fishes of the region pretty well, but I never found any of them behaving as Grant suggests, even back from the sounds in the fresh-water inlets. I also spent four summers at the Carnegie Institution Laboratory, Dry Tortugas, Florida, and watched fishes there in the shallow bays and inlets in the coral islands, but I have never seen

anything like this explanation of Grant's nor have I found anything in the literature, although I have been a fish bibliographer for forty years."

Meteor craters--WATSON [1936] prepared a general report on craters formed by meteorites about half of which is devoted to the Carolina Bays. Unfortunately his most important discussion, that on Meteor Crater, Arizona, is based on old reports, the latest being a short paper in the Scientific American in 1927. In this paper the meteorite which formed Meteor Crater is shown in a figure as resting well under the rim, and marked, "Supposed position of meteoric body." Actually the meteoric body was located entirely inside the present crater by JAKOSKY and Others [1932]. And as has already been explained, this meteorite formed an elliptical crater, and it did not explode.

Watson states that this meteorite came in at an angle of 45° with the horizontal. Actually, as judged from the findings of Jakosky, this meteorite must have come in at a much greater angle, probably near 70° with the horizontal. This would account for the small ellipticity of Meteor Crater, Arizona.

Watson mentioned again and again the "explosion" of a meteorite when it strikes the Earth. The writer knows of no evidence presented in the literature which leads to the conclusion that such an explosion would or did take place. The largest meteorite seen to fall, fell in Siberia on June 30, 1908. According to a report by OLIVIER [1930] and to one by NININGER [1933] the area was visited by L. A. Kulik in 1927 and in 1928. In an area some two miles in diameter were found 200 craters varying from those a yard or two in diameter to one more than 50 yd across. Interestingly enough no meteorite fragments were found until the second visit in 1928; therefore they must have been very scarce. Neither the account nor the photographs of the area give any evidence of an explosion even for the largest craters.

WATSON [1936] suggests that the meteorites found in the Appalachian Mountain region could not be a part of the supposed meteorite shower that formed the Carolina Bays, because that shower occurred so long ago that the meteorites would have disintegrated completely. If this suggestion is correct, then it can explain the lack of meteorite fragments in the area of the present Carolina Bays.

Since the bays undoubtedly have been modified by lake wave action and wind-blown sand for many centuries, the change of ellipticity with size cannot mean very much; in fact when ellipticity is plotted as a function of size the points are so scattered that it is not possible to determine how to draw a curve through them. Since there is no experience and no theory to the contrary, it may be that elliptical meteorite scars should not show a change of ellipticity with size even though all meteorites come in at the same angle.

Even though most meteorite craters (and supposed meteorite craters) are nearly circular, this does not prove that very large meteorites such as may have struck the Carolinas, could not have come in at relatively small angles to the horizontal and formed elongated scars which became lakes that acquired rather smoothly elliptical outlines.

Other objections raised by Watson have been answered elsewhere in this paper by the writer. Watson concludes his paper with: "It is, therefore, impossible to accept the theory of the meteorite origin of the Carolina Bays." In the writer's opinion Watson has presented no convincing evidence, or interpretation of evidence, which would compel one to draw that conclusion.

Summary--The writer has re-examined all important reports concerning the origin of the Carolina Bays to see if he could show the possibility or impossibility of an explanation based on a modified meteorite theory of origin which he has suggested. JOHNSON [1942], has presented a most valuable, complete and critical review of all reports bearing on the subject published before 1942, and has also added much new information, including a detailed discussion of his "Hypothesis of complex origin." Johnson lists 29 "Requirements of a satisfactory hypothesis" and shows that his theory meets these tests.

The writer has applied these 29 tests to a meteorite theory of origin and has found that not a single one of the tests ruled out such a theory.

The writer has shown that Johnson's theory of complex origin is untenable because certain of his assumed and absolutely necessary geologic conditions do not exist, and because his theory violates the principle of the conservation of energy.

The writer has found no important evidence, or logical interpretation of evidence, which makes a meteorite theory of origin of the Carolina Bays untenable.

Conclusions--At the present time it appears to be impossible to set up a sufficiently critical set of specifications which a satisfactory theory of origin of the Carolina Bays must meet.

A completely satisfactory theory for the origin of the Carolina Bays has not yet been presented.

At the present time a meteorite theory of origin of the Carolina Bays appears to be the least unsatisfactory of all theories that have been published.

One is forced to the conclusion that subsurface investigations over a number of typical Carolina Bays must be made before a satisfactory explanation of their origin can be written.

Acknowledgment--The writer is pleased to acknowledge the assistance and encouragement of his colleague, F. A. Melton of the University of Oklahoma Department of Geology, in the preparation of this paper.

References

COOKE, C. WYTHE, Discussion of the origin of the supposed meteorite scars of South Carolina, J. Geol., v. 42, pp. 88-96, 1934.

COOKE, C. WYTHE, Elliptical bays in South Carolina and the shape of eddies, J. Geol., v. 48, pp. 205-211, 1940.

COOKE, C. WYTHE, Elliptical bays, J. Geol., v. 51, pp. 419-427, 1943.

COOKE, C. WYTHE, Neptune's racetracks, Sci. Mon., v. 60, pp. 286-291, 1945.

GRANT, CHAPMAN, A biological explanation of the Carolina Bays, Sci. Mon., v. 61, pp. 443-450, 1945.

GUDGER, E. W., Letter to editor, Sci. Mon., v. 62, p. 394, April 1946.

HUMPHREY, W. J., Physics of the air, 3ed ed., McGraw Hill, 676 pp., 1940.

JAKOSKY, J. J., quoted from Engineering and Mining Journal by The Library Digest, p. 13, issue of August 6, 1932.

JAKOSKY, J. J., C. H. WILSON, and J. W. DALY, Geophysical examination of Meteor Crater, Arizona, Geophys. Prospecting, Trans. Amer. Inst. Min. Metal. Eng., pp. 63-98, 1932.

JOHNSON, DOUGLAS, The origin of the Carolina Bays, Columbia Univ. Press, New York, 341 pp., 1942.

MELTON, F. A., Reply to discussion (by Cooke) of the origin of the supposed meteorite scars of South Carolina, J. Geol., v. 42, pp. 97-104, 1934.

MELTON, F. A., and SCHRIEVER, W., The Carolina Bays--Are they meteorite scars?, J. Geol., v. 41, pp. 52-66, 1933.

NININGER, H. H., Our stone-pelted planet, 235 pp., Houghton Mifflin, New York, 1933.

OLIVIER, CHARLES P., Comets, 246 pp., Williams and Wilkins, Baltimore, 1930.

STEPHENSON, L. W., Deep well at Charleston, S. C., U. S. Geol. Surv., Prof. Paper 90-H, pp. 69-90, 1915.

WATSON, FLETCHER, JR., Meteor craters, Popular Astron., v. 44, pp. 1-16, 1936.

Physics Department,
University of Oklahoma,
Norman, Oklahoma

(Manuscript received May 1, 1950, and, as revised, November 2, 1950; presented at the Thirty-First Annual Meeting, Washington, D. C., May 3, 1950; open for formal discussion until July 1, 1951.)

REPORT OF THE SPECIAL COMMITTEE ON THE GEOPHYSICAL AND GEOLOGICAL STUDY OF THE CONTINENTS 1949-1950

G. P. Woollard, Chairman

C. S. Beals
Francis Birch
Walter H. Bucher
Maurice Ewing
R. A. Geyer
R. W. Goransen
Ross Gunn
Sigmund I. Hammer
H. W. Hemple
Harry H. Hess
Patrick M. Hurley
Henry R. Joesting
Chester R. Longwell
J. B. Macelwane
H. A. Marmer
Frank Neumann
B. Perkins, Jr.
E. B. Roberts
D. C. Skeels
N. C. Steenland
W. T. Thom, Jr.
J. Tuzo Wilson
J. Lamar Worzel

Introduction--During the year 1949-1950 the activities of the Committee varied from its collective action in sponsoring a field program of gravity and magnetic measurements in the United States to securing the release of regional gravity data for general scientific use from the major oil and exploration companies. The activities of the individual committee members working in their own lines of specialization embraced practically all of the methods of geological and geophysical study. The amount of data obtained was probably greater than that obtained in any previous year, but even more gratifying was the increase in interest shown by government agencies and the universities in pursuing investigations having a bearing upon the structure of the continents and their history.

Gravity investigations--One of the projects initiated by the Committee in 1940 and supported by grants-in-aid from the Geological Society of America which was completed during the past year was the regional gravity and magnetic reconnaissance survey of the Appalachian Mountains. Although work on this project was interrupted by the War, over 6000 sets of observations were made covering the area of the Eastern Seaboard between the Maritime Provinces of Canada and the Gulf of Mexico. The gravity data have been reduced to yield Bouguer anomalies, and an isoanomaly map with ten-milligal contours prepared incorporating these and other gravity data observed by the Dominion Observatory in Canada, the Gulf Research and Development Co. in Pennsylvania and West Virginia, J. B. Hersey in Pennsylvania, the Humble Oil and Refining Co. in the Gulf of Mexico Coastal Plain and the Carter Oil Co. in the Cape Hatteras region of Virginia. This investigation, the first complete gravity study of an entire mountain system, would not have been possible without the financial support of the Geological Society of America and the loan of a gravity meter by the Humble Oil and Refining Co. to the Committee.

Other regional gravity data that became available during the year were primarily from commercial exploration sources. Through the efforts of the Committee a fairly complete regional coverage of gravity data on an eight- to ten-mile station spacing for the Gulf Coast and Mid-Continent regions was obtained. These data which include a large percentage of the material given to the U. S. Coast and Geodetic Survey on a confidential basis for special studies connected with national defense, will be released for general scientific use through the Geodetic Division of the U. S. Coast and Geodetic Survey as soon as they have been adjusted to absolute datum. Companies that released data to the Committee were the following:

Humble Oil and Refining Co.	Sun Oil Co.
Shell Oil Co.	Magnolia Petroleum Co.
Ohio Oil Co.	Brown Geophysical Co.
Esso Standard Oil Co.	Gulf Research and Development Co.

Other regional gravity data outside of the United States were secured from the Socony Vacuum Oil Co. and Gravity Meter Exploration Co.

Regional gravity data for areas other than the above to be released through publication are: Oklahoma, Wyoming, and parts of South and North Dakota, Montana, Utah, Colorado, and Texas by Paul Lyons of Carter Oil Co., the state of Colorado by Ralph Holmer of the Colorado School of

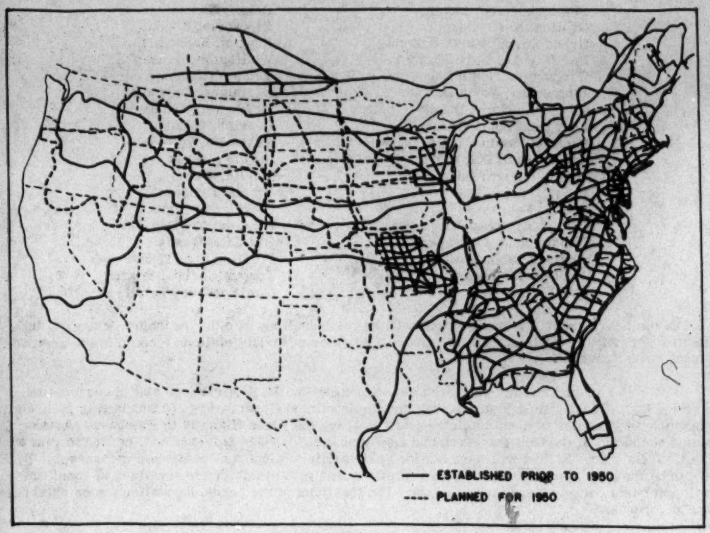


Fig. 1--Regional reconnaissance gravity traverses in the United States

Mines, the province of Alberta, Canada by Gravity Meter Exploration Co., eastern Kansas and Oklahoma by the U. S. Coast and Geodetic Survey, central Vermont and New Hampshire by R. J. Bean of Harvard University.

Somewhat more limited gravity investigations that have come to the attention of the Committee are as follows: a regional network of stations in Michigan by James T. Wilson of the University of Michigan, a survey of eastern Pennsylvania and adjacent New Jersey by William Bonini and Dudley Meier of Princeton University, part of the New Jersey Coastal Plain by Charles Drake of Columbia University, a detailed survey of part of Missouri by Garland and Chandlok of St. Louis University, traverses in central Pennsylvania by Lloyal O. Bacon of Pennsylvania State College, the Mt. Prospect igneous complex in western Connecticut by N. C. Harding of the University of Wisconsin, the Madison Quadrangle, Wisconsin by Virgil Mann of the University of Wisconsin, and traverses between the Wasatch Mountains and Quirrh Mountains in Utah by H. V. W. Donohoo of the University of Utah.

Gravity work now in progress under the auspices of the Committee and supported by the Geological Society of America by a grant-in-aid includes the development of a reconnaissance network of regional traverses covering the northwestern part of the United States. Stations are being set at approximately ten-mile intervals on the principal highways and the survey is being tied across the Canadian border to a similar network of gravity traverses established by the Dominion Observatory. Traverses established to date and those now in progress on this program are indicated in Figure 1.

Current gravity work by other groups of particular interest is the north-south line of 35 pendulum stations with gravity meter inter-station ties that is now being established by the U. S. Coast and Geodetic Survey between Winnipeg, Canada and Mexico. It is believed that this line of stations will be the most accurately determined group of gravity stations established to date by U.S. C. and G. S. It will serve not only as a base line through the middle of the country but also as a calibration range for establishing the linearity and scale constant of gravity meters. Stations are being located at the following places:

Pembina, North Dakota	Beloit, Kansas
Grafton, North Dakota	Ellsworth, Kansas
Grand Forks, North Dakota	Newton, Kansas
Devils Lake, North Dakota	Wellington, Kansas
Carrington, North Dakota	Tulsa, Oklahoma
Jamestown, North Dakota	Okmulgee, Oklahoma
Ellendale, North Dakota	McAlester, Oklahoma
Aberdeen, South Dakota	Dension, Texas
Redfield, South Dakota	Saline No. 2, Texas
Huron, South Dakota	Kerens, Texas
Mitchell, South Dakota	Merlin, Texas
Tyndall, South Dakota	Bryan, Texas
Neligh, Nebraska	Cleveland, Texas
Fullerton, Nebraska	Houston, Texas
Grand Island, Nebraska	Bay City, Texas
Hastings, Nebraska	Port Lavaca, Texas
Red Cloud, Nebraska	Corpus Christi, Texas
	Sam Fordyce, Texas

Of the above group, 23 observations will be reoccupations of older pendulum stations.[4] In addition, gravity meter ties are to be made to 20 other pendulum stations located in the area adjacent to the traverse.

Under the auspices of the Research Directorate of the U. S. Air Force and in cooperation with the U. S. Coast and Geodetic Survey and the Dominion Observatory of Canada it is planned to establish another line of pendulum observations along the Alcan Highway to Fairbanks, Alaska with a pendulum of the Gulf Research and Development Co. This traverse will be tied to that of the U. S. G. and G. S. and will have stations primarilly at airports. Pendulum measurements are to be made at approximately 150-mi intervals and gravity meter observations at about ten-mile intervals between pendulum stations. The locations of the pendulum stations to be established are as follows:

Great Falls, Montana	Fort Nelson, British Columbia
Cut Bank, Montana	Liard Nelson, British Columbia
Lethbridge, Alberta	Watson Lake, Yukon
Calgary, Alberta	Teslin, Yukon
Red Deer, Alberta	White Horse, Yukon
Edmonton Alberta	Burwash Landing, Yukon
Athabaska, Alberta	Northway, Alaska
Kinuso, Alberta	Big Delta, Alaska
Grand Prairie, Alberta	Fairbanks, Alaska
Fort St. John, British Columbia	Gakona, Alaska
Skanni Chief, British Columbia	Anchorage, Alaska

Of the above, six stations will be reoccupations of Dominion Observatory pendulum stations. The purpose of this line of pendulum measurements, which it is hoped can be extended into Mexico, is to provide a line of easily accessible gravity bases at airports which can be occupied during the short period an airplane is on the ground at stops on a continuing flight. Such a line of stations will furnish a quick method of calibrating the high range gravity meters now being developed for geodetic work, and also serve as a base line running the length of the continent for tying gravity surveys in Mexico, the United States, Canada, and Alaska together. It is hoped this line of stations will resolve the reported two-milligal discrepancy between the United States and Canadian datum values and the seven-milligal discrepancy between the United States and Mexican datum values based on gravity meter ties between Ottawa, Washington, and Mexico City.

In South America, gravity observations were made this past year by G. R. Shelton of the U. S. Coast and Geodetic Survey working in cooperation with the Inter-American Geodetic Survey and by N. C. Harding of the University of Wisconsin Department of Geology working under the auspices of the Office of Naval Research. The measurements carried out by the U. S. Coast and Geodetic Survey involved pendulum observations at most of the capital cities in South America and the establishment of a gravity base at the Inter-American Geodetic Survey headquarters in Balboa, Canal Zone. Harding's measurements made with a high range Worden geodetic gravity meter using airplane transportation followed the network shown in Figure 2. In addition to ties to the national base stations the stations established by G. R. Shelton and the trans-continental gravity

Fig. 2--Routes of global gravity network in the Western Hemisphere

traverses established by Paul Wuenschel of Columbia University in South America, Harding made local gravity surveys in cooperation with university and government groups in Brazil, Venezuela, Argentina, Panama, and Puerto Rico. He also established a traverse across Mexico from Acapulco to Tuxpan and made ties at Fairbanks and Anchorage, Alaska to the gravity traverses established this past year there by Paul Wuenschel along the Richardson and Streese Highway.

In Canada C. S. Beals, Director of the Dominion Observatory, advises that the gravity program over the past year consisted of an extensive series of gravity meter investigations in the area west of Hudson Bay, in southern Ontario and in Quebec. The development of the Canadian network of gravity stations is shown in Figure 3. The program for this year will include gravity meter work in the Maritime Provinces, eastern Quebec, Newfoundland and possibly Baffin Land.

In connection with the global network of gravity stations being established under the auspices of the Office of Naval Research and directed by the Chairman of the Committee, C. Mackenfuss of the University of Wisconsin is making a series of measurements in the South Pacific including the islands of Samoa, Fiji, New Caledonia, New Hebrides, New Zealand, and New

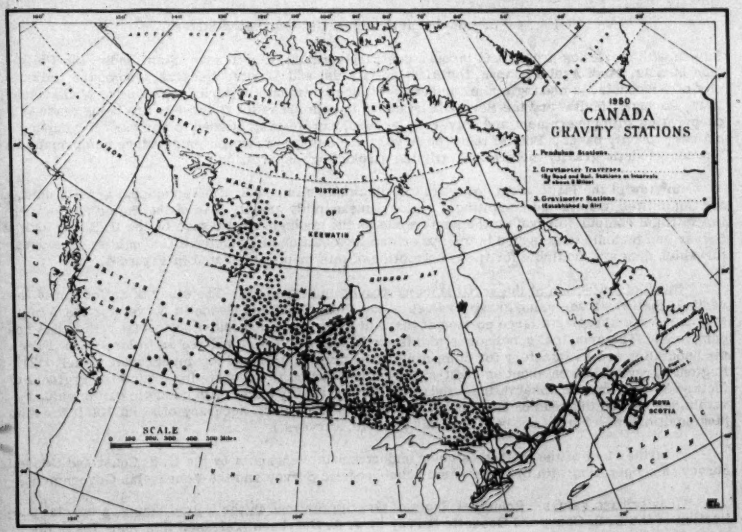


Fig. 3--Network of Canadian gravity stations

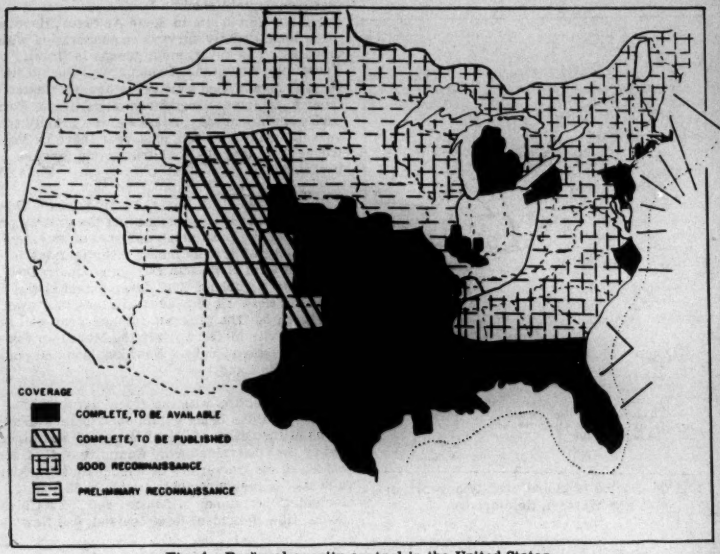


Fig. 4--Regional gravity control in the United States

Guinea with traverses around and through central Australia, ties to Java, Siam, India, the Philippine Islands, Saudi Arabia, Japan, the Aleutian Islands, and Alaska. Harding, also of the University of Wisconsin, is making a similar series of measurements in Africa with ties to Madagascar, Italy, Portugal, Malta, and the Bermuda Islands. In both areas local surveys are being made in cooperation with government and university groups, and ties established to various oil company primary gravity bases. Both of these observers are using high range temperature compensated Worden geodetic gravity meters and utilizing airplane transportation.

In view of the large areal coverage for which there is now available regional gravity data, the Committee has started compiling a regional isoanomaly gravity map of the United States with ten-milligal contour interval on the same scale as the geologic map issued by the U. S. Geological Survey and tectonic map issued by the American Association of Petroleum Geologists. The area for which data are available for the construction of this map is indicated in Figure 4.

Study of deflection of the vertical using gravity observations--The study of deflection of the vertical that was made using gravity values of the U. S. Coast and Geodetic Survey for the Army Map Service embracing a large portion of the Gulf Coast area and Mid-Continental region has been completed. The principal conclusions of this study are of interest and are as follows: (1) Free air anomalies are satisfactory for computing deflections in areas of low topographic relief. (2) Regional gravity data on about an eight-mile station spacing is adequate for evaluating regional effects. (3) Astronomic observations reduced gravimetrically agree with geodetic datum values within one second in areas of low topographic relief. (This is an accuracy of about 100 ft for mapping positions which have not been tied into geodetic surveys.)

A further test of the method is being undertaken in Venezuela by the U. S. Coast and Geodetic Survey in cooperation with the Inter-American Geodetic Survey and the Venezuelan Government.

Gravity base values--Principal Facts of Gravity Stations in the United States, a special publication of the U. S. Coast and Geodetic Survey by J. A. Duerksen, released this year, takes the place of eight separate publications previously issued. It includes principal facts and description

of all pendulum bases in the United States, and the early stations based on the New Jersey Avenue base value in Washington, D. C. have been corrected to the present Commerce Building base value.

Gravity over the continental margin--Under the auspices of the Office of Naval Research a considerable amount of gravity work across the Continental Shelf has been done by groups from Columbia University and the U. S. Geological Survey. Using Vening Meinesz pendulums on loan from the Woods Hole Oceanographic Institution and traveling in a U. S. Navy submarine, the Columbia University group have carried out the following program: 104 observations on seven profiles between Cape Hatteras, North Carolina; and Nova Scotia; 117 observations on eight profiles between Key West, Florida and Cape Hatteras, North Carolina; 276 observations on 12 profiles in and around the Bahama Islands; 142 observations along the coast from San Diego, California to the Aleutian Islands and in the Bering Sea and Chukchi Sea; 68 observations between San Diego, California and the Panama Canal; 70 observations on seven profiles between Valparaiso, Chile and Panama; 56 observations on six profiles between Panama and Trinidad.

None of the above data have been published as yet although some are in preparation for publication. On the three traverses made across the Continental Shelf off the Louisiana-Texas Coast by the U. S. Geological Survey using a gravity meter in a diving bell, a preliminary anomaly map has been prepared and placed on open file for inspection, and a final report is in preparation.

Magnetic investigations--Under the auspices of the Committee measurements of the vertical component of the Earth's magnetic field were made as part of the program of regional gravity measurements previously described covering the Appalachian Mountain system and the northwestern part of the United States. Similar sets of measurements are also being made along the traverses to Fairbanks, Alaska on the Alcan Highway. This same procedure also has been followed by the Dominion Observatory of Canada on their regional reconnaissance traverses. At this time, however, none of the magnetic results has been worked up.

The aeromagnetic total intensity surveys conducted by the U. S. Geological Survey are best summarized in Figure 5 which shows the surveys completed, those in progress and those planned as of January, 1950. Similar surveys have also been made by commercial exploration groups in the United States but these data on the whole are not available.

Although the exact extent of aeromagnetic surveys in other areas is not known, it is believed that possibly several hundred thousand square miles have been covered in Canada. Part of this work has been carried out by the Geological Survey of Canada and the results of these investigations are being prepared for general release.

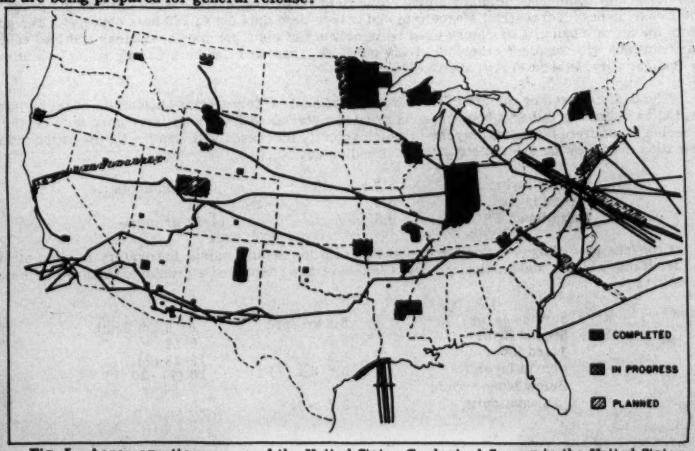


Fig. 5--Aeromagnetic surveys of the United States Geological Survey in the United States

Of interest in the handling of magnetic data is the adoption of IBM machines by the U. S. Coast and Geodetic Survey for processing the voluminous material secured from their magnetic observatories. There are two continuously recording observatories in the United States, three in Alaska, and one each in Puerto Rico and Hawaii. In addition to the observations from these stations, the U. S. Coast and Geodetic Survey also secured data from 68 field stations in the United States, 36 in Alaska and 40 in Central America and South America during the past year.

Magnetic base values and maps--Special reports issued during the year by the U. S. Coast and Geodetic Survey that are of interest include U. S. Magnetic Tables and Charts for 1945, Serial 667. This publication, which appears at ten-year intervals, gives the principal facts for the magnetic components in the United States. The present edition differs from earlier editions in that tabulor observational data are presented only for those stations reoccupied for compiling the 1945 revised maps. Earlier editions included observational data for all stations whether they were used for the revisions or not. Serial 690, Magnetic Observations in the American Republics 1945-1948 supplements an earlier report on magnetic investigations in Central and South America. Serial 717, Magnetic Declination in Texas, 1940, presents a special isogonic map of Texas. Magnetic charts in preparation by the U. S. Coast and Geodetic Survey which are nearing completion are the 1950 isogonic charts of the world, the United States and Canada.

Aeromagnetic maps published during the year by the U. S. Geological Survey are: eight sheets covering the lead and iron district of southeastern Missouri and accompanying profiles; 12 sheets covering 9250 sq mi in north central Minnesota; 26 sheets covering 10,000 sq mi in northern Indiana; and a series of profiles covering 800 sq mi in northern Michigan.

Aeromagnetic maps placed on open file during the year by the U. S. Geological Survey are: 42 sheets covering 17,000 sq mi in northern and western Indiana; 18 sheets and accompanying profiles covering 24,000 sq mi in northern Minnesota; and eight sheets covering Great Sitkin, Adak and Umnak Islands, Alaska. All these maps may be examined at the Survey Office in Washington. The Indiana and Minnesota maps may also be examined at various depositories in the respective states.

Seismic investigations--The studies of the blast from the explosion of 156,000 lb of nitramon at Corona, California by W. S. Rooney, Howard Tatel, and M. A. Tuve of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington, and by B. Gutenberg and C. F. Richter of the Seismological Laboratory of the California Institute of Technology are of extreme interest. This explosion was recorded by both standard earthquake recording equipment and portable vertical and horizontal component seismometers. Nine field recording stations were used by the group from the Department of Terrestrial Magnetism and travel-time data out to 150 kms obtained. The group from the Seismological Laboratory used their network of eight permanent stations and four temporary stations with supplementary data from the U. S. Coast and Geodetic Survey seismic stations at Boulder City, Pierce Ferry, and Overton.

The data obtained by the group from the Department of Terrestrial Magnetism could be interpreted as indicating either a homogeneous crustal material with velocity increasing with depth, or a series of discrete horizontal layers in which velocity increased with depth. On the latter interpretation the following crustal structure was indicated.

Surface layer	5.7 km/sec	0- 3 km depth
Second layer	6.3	3-14
Third layer	6.8	14-22 or more

From the recordings obtained by the group from the Seismological Laboratory for this blast and from other blasts and earthquake data Gutenberg has postulated a crustal structure for the area as follows,

Surface layer	5.8 km/sec	0- 6 km depth
Second layer	6.5	6-12
Third layer	5.6	12-18 (?)
Fourth layer	5.6-8.1 (?)	18 (?) -30 (?)
Below Mohorovicic Discontinuity	8.2 > 34	.....

Although it is not possible to verify the existence of the low velocity 5.6 km/sec layer at depth from surface blast data, it does appear significant that for the first time the near surface velocity structure obtained from surface blast measurements and earthquake data are in substantial agreement. Part of the discrepancies in structural interpretations hitherto reported between surface blast data and earthquake data, however, are undoubtedly caused by the fact that the concept of horizontal layering in the crust is not strictly true. It is well established that crustal layers thicken beneath mountain ranges, and if the mass distributions suggested by the regional gravity anomalies that are now becoming available have any significance, crustal structure is indeed complex.

It is hoped that the current seismic refraction investigation now being conducted by John E. Hodgson of the Dominion Observatory, the seismic refraction and reflection studies being made by the group at the Department of Terrestrial Magnetism of the Carnegie Institution of Washington, and the seismic reflection studies of deep crustal structure that have been started by Judson Mead at the University of Indiana will contribute substantially to a better understanding of the true nature of the layering in the Earth's crust.

Other current seismic studies that are of interest from the standpoint of geology are those being conducted across the Hudson River Valley above New York City and on Long Island by the group at Columbia University. These investigations should yield considerable valuable information about the crystalline basement surface and overlying sediments in this area.

Seismic investigations on the continental margin--The offshore seismic work by the group at Columbia University under the direction of Maurice Ewing and started under the auspices of the Geological Society of America is being continued under the auspices of the Office of Naval Research. To date three seismic refraction traverses have been established across the Continental Shelf out to 1500 fm and two traverses out to the edge of the shelf. These traverses running essentially perpendicular to the coast line originate from Portland, Maine, Woods Hole, Mass., New York City, Cape May, New Jersey and Norfolk, Virginia. The development of a satisfactory technique for making seismic refraction measurements in deep water this part year permitted an oceanic traverse to be established to Bermuda. Using Bermuda as a central terminal point new traverses are planned to Argentina, Newfoundland, Woods Hole, Mass., New York City, Charleston, S. C., Miami, Fla. and San Juan, Puerto Rico. As the earlier work showed a definite change in the lithology of the basement rock in the continental and oceanic areas as revealed by seismic velocities, these traverses should define the boundary of the continental block and also the nature of the transition.

Other seismic work started on the Pacific Coast bearing upon the same problem is that of R. Raitt at the Marine Physical Laboratory at San Diego, California. Raitt established a seismic refraction profile this summer from San Diego to Bikini Atoll and the results from this investigation are being anticipated with a great deal of interest.

Tectonic investigations--During the year the U. S. Coast and Geodetic Survey made a series of special surveys in several areas along the San Andreas Fault in California to determine the amount of horizontal movement. These measurements included reobservation of existing triangulation nets, astronomic azimuths and leveling. Some of the results are as follows.

Castle Mount Triangulation Station
Azimuths changed clockwise 5".3 between 1885 and 1923
2".2 between 1923 and 1949
64 year change = 7".5 clockwise

Elk Triangulation Station
Azimuths changed clockwise 1".5 between 1923 and 1949

Also of interest are the results obtained by the U. S. Coast and Geodetic Survey on local subsidence and horizontal movement at Terminal Island, California. Horizontal movements as great as one foot were found with a systematic displacement of surface marks toward the center of the area of subsidence. The vertical movement recorded exceeded ten feet. Similar measurements are also being carried out in the Lake Mead area of Nevada and Arizona by the U. S. Coast and Geodetic Survey to determine the movement caused by the weight of water impounded by the Hoover Dam.

In the study of eustatic changes as reflected in the tide gage readings there is a distinct handicap in that outside of the work carried on under the asupices of the U. S. Coast and Geodetic Survey there is no adequate system for maintaining a reference datum. Tide staffs are replaced for the most part without reference to level line bench marks. Where bench marks are used, there is

generally only one reference which is apt to be a poor one in dock areas because of the prevalence in such areas of "made" ground that is constantly settling. This has been demonstrated repeatedly by observations at tide stations of the U. S. Coast and Geodetic Survey where three bench marks are commonly used in establishing the datum of tide staffs. Because of this defect, it is only possible to use relatively recent data (past 40 yr) that have been accumulated in North America waters under the control of the United States for evaluating changes in sea level.

On the basis of the data obtained from 34 tide stations on the Atlantic Coast, 18 on the Pacific Coast, ten in the Gulf of Mexico, 12 in Alaskan waters, and one in Panama, it appears that for the period 1900 to 1929 mean sea level remained essentially constant. Since 1929, however, there has been a marked rise in sea level at essentially a mean constant rate in all areas except Alaskan waters where mean sea level has remained constant. From the Gulf of Mexico to Boston, sea level is rising at the rate of 0.02 ft/yr. North of Boston the rate decreases. On the Pacific Coast from Panama to Seattle the rate is about 0.007 ft/yr or roughly one-third that observed in the Gulf of Mexico and along the Atlantic Coast. North of Seattle the rate decreases to essentially zero in the Aleutian Islands. These changes in sea level may reflect crustal warping or be related entirely to large scale meteorological changes affecting the oceanic circulation and topography. A detailed report on this work is being prepared by H. A. Marmer of the U. S. Coast and Geodetic Survey.

Geological investigations--A tectonic map of Canada similar to that prepared by the American Association of Petroleum Geologists for the United States is now being prepared by the Geological Association of Canada in cooperation with the Geological Survey of Canada and the Geological Society of America. The geological map of South America prepared under the auspices of the Geological Society of America has been completed and is now being distributed. The combination of this map and the geological map of North America also prepared under the auspices of the Geological Society of America gives the most authoritative regional geologic picture of the western hemisphere available.

W. T. Thom, Jr., of Princeton University has advised that he has started revising the crystalline basement surface map of the United States he originally prepared under the auspices of the Committee in 1939. The additional deep-well data accumulated in the interim and the seismic exploration data being made available to him for this revision will make this map one of the most valuable contributions to the study of the continents since the appearance of his first map.

Those familiar with the geologic studies of J. Tuzo Wilson of the University of Toronto in the Canadian Shield will be interested to know that he spent the summer of 1950 in Africa and Australia studying the shield geology of these areas. All interested in an excellent resume of the problems of studying the structure of the continents are strongly urged to read his recent paper, Recent Applications of Geophysical Methods to the Study of the Canadian Shield, [Trans., Amer. Geophys. Union, v. 51, pp. 101-114, 1950].

Other methods of study--New material that has come to the attention of the Committee in the field of radioactive age determinations beyond that reported on in last years report is the program now being conducted by Laurence Kulp of Columbia University. Apparatus has been constructed at the Lamont Geological Observatory of Columbia University for absolute age determinations of rocks using the U-He, U-Pb, Rb-Sr, Ionium, Strontium Isotope Ratio, and Carbon 14 methods. Major emphasis at the present is on the study of deep sea core samples using the Ionium and Carbon 14 methods. Work has also been started on carbonate rocks using the strontium isotope ratio method. No new work in the study of thermal gradients beyond that covered in last year's report has come to the attention of the Committee.

Committee objectives--At a meeting of the Committee held in the Reading Room of the National Academy of Sciences Building on the afternoon of May 2, 1950, and attended by a majority of the Committee, the objectives of the committee were discussed and redefined. The following were agreed upon:

(a) Obtain data of scientific value related to the geologic and geophysical study of the continents from any and all sources, and deposit these data in a federal depository which will make them generally available.

(b) Aid university groups with demonstrated responsible personnel in obtaining the loan of geophysical equipment for scientific investigations.

(c) Foster surveys of a scientific nature in areas that are not apt to be explored on a commercial basis in the search for natural mineral resources.

(d) Foster surveys, traverses, or tie lines crossing international boundaries that constitute a barrier for government operated survey parties.

(e) Acquaint scientists through the medium of the Annual Report of this Committee in the Transactions of AGU with the activities of different groups in various allied fields of research working in various areas so that scientific programs can be better coordinated.

(f) Foster the publication of a brief resume of preliminary scientific results particularly where there is apt to be a considerable delay before the publication of a complete final report.

(g) Prepare and make available maps and charts representing up to date compilations of data related to the geological nnd geophysical study of the continents.

Department of Geology,
University of Wisconsin,
Madison, Wisconsin

(Communicated manuscript received March 15, 1950, and, as revised, September 11, 1950; open for formal discussion until July 1, 1951.)

Transactions, American Geophysical Union Volume 32, Number 1 February 1951

INTERNATIONAL COOPERATION ON A GEODETIC PROJECT

Floyd W. Hough

The term "cooperation" is one of the most satisfying and comprehensive words in the English language. If we were to have complete cooperation in all matters between individuals and nations, the acme of human aspiration would be reached; selfishness would be abandoned; universal peace would be a fact; the millenium would be at hand. Unfortunately, human nature and human reactions are such that progress toward the attainment of this perfection in human relations is disheartenlingly slow. In fact, it appears at times that progress gives way to retrogression in the political and economic fields - not so, in the scientific.

We in the field of geodesy may well take pride in the fact that since the end of World War II there has been a very high degree of international cooperation, particularly in the Americas and in Western Europe. In the Americas, this cooperation has been extensive along the lines of geodetic field operations, exchange of ideas, methods, and instrumental equipment, and in computational work. In Western Europe, where almost complete coverage of highly accurate geodetic field surveys has been an accomplished fact for many years, international cooperation has taken the form principally of a highly complex least-squares adjustment of a network of first-order triangulation, covering the entire western area of the European Continent, along with a portion of northwest Africa. Twelve nations have worked together on this project.

This paper deals exclusively with geodetic cooperation in Europe. The historical and operational details of the European Adjustment have been covered in prior papers on this subject and will only be summarized here. Suffice it to say that the adjustment was initiated in 1945, at Bamberg, Germany, by an intelligence team of the Office of Chief of Engineers, United States Army. This team had succeeded in locating the Trigonometrical Section of the Reichsamt für Landesaufnahme at the recently captured town of Friedrichsroda located in the German Province of Thuringia. The chief of this organization, internationally known geodesist Erwin F. Gigas, with a number of his staff, records and equipment, was moved by military order to Bamberg in the U. S. Occupation Zone. Gigas was directed to begin at once a rigorous least-squares adjustment of a selected network of first-order triangulation, extending over 300,000 sq mi of Central Europe. In order to make certain that the adjustment would be satisfactory and yet could be completed within a two-year period, the Bowie junction method was chosen. This method of adjustment had proved both practical and adequate in the United States. Following a thorough study of the old triangulation survey records, the adjustment itself was undertaken and carried through to completion in June, 1947.

The first-order triangulation of Europe had been done over a period of the last two hundred years, each sovereign nation working within its own borders and, by agreement, connecting to its neighbors' triangulation at the frontiers. National pride of sovereignty dictated that each country must establish its own datum independent of every other country. This datum was usually established in the capital of the country by the acceptance of an astronomic fix for one station. With no attempt to minimize the effect of the deflection of the vertical at the initial station, it is obvious that disparities in horizontal position at the common frontier points should be expected. These differences often amounted to several hundred meters. Owing to the measurement and remeasurement of angles over a long period of years, the accuracy of the basic triangulation nets of most of the European countries is of a very high order. The potential value to the scientific study of the geoid of a complete least-squares adjustment of the entire continental triangulation on a common geodetic datum had been recognized by European geodesists for many years. Unfortunately, because of national jealousies, a comprehensive project of this type for all Europe had been impossible. A notable exception was the agreement among the Baltic countries some thirteen years ago to adjust the so-called Baltic Ring. This adjustment of the triangulation around the Baltic Sea was accomplished by the Baltic Commission with much success and the resulting positional closures were excellent.

With the adjustment of the Central European Area by the German group at Bamberg well underway in May 1946, it appeared that the time had arrived when a major contribution to the study of the figure of the Earth might be made by a rigorous mathematical adjustment of the first-order triangulation of the entire European continent. The Hayford, or International, Ellipsoid, which had been

accepted at Madrid in 1924 by the International Union of Geodesy and Geophysics as representing the geometric figure most closely fitting the undulations of the whole geoid, was computed entirely on the basis of the first-order triangulation in the United States. This limitation was not because no other mass of triangulation of that accuracy existed elsewhere in the work but simply because in no other place had extensive arcs of triangulation been adjusted and computed on a common geodetic datum, with lengths referred to the International Meter. The European adjustment, with numerous astronomic stations, now offered an opportunity to determine whether in fact the Hayford Ellipsoid is the figure best fitting the geoid in Europe. This additional area, together with further extensions of common datums in Asia and international datum-connections by newly developed methods, would make possible a redetermination of what should be a better mean geometric figure on which to calculate relative positions from measurements on the geoid.

In May, 1946, a representative of the Army Map Service visited Switzerland, Denmark, The Netherlands, Belgium, and France to consult with the leading geodesists of those countries in an effort to enlist their support in an immediate proposal to extend the Central European Adjustment to all of Western Europe. Their reaction was not only favorable to cooperation but they urged that an international conference be called in August to explore the matter further. The preliminary meeting in August, 1946, in Paris, was followed by a second conference in October, 1947, also in Paris, called by the Central Bureau of the International Association of Geodesy. At the 1947 meeting, the desire of delegates of the eleven western countries to proceed with the adjustment was very evident. It was agreed that the adjustment should be accomplished in two phases: the first phase would establish a mathematically consistent least-squares adjustment of the first-order triangulation of the continent, all on the Central European datum and computed on the International Ellipsoid; the second and more scientific phase would follow in which the small discrepancies between the geoid and the ellipsoid would be taken into account.

At the 1947 conference, a stalemate developed when the representatives of the eleven nations present declined to permit the German group at Bamberg to extend the adjustment into Western Europe. Considering the animosities arising from the recent War, this attitude was not surprising. Immediately following the adjournment of this meeting, the Army Map Service representative made a proposal to the Secretary of the Central Bureau of the International Association of Geodesy, later confirmed by the Chief of Engineers, whereby the Army Map Service would be responsible for the first phase of the adjustment in Western Europe under the auspices of the International Association, the work to be carried on in Washington. A condition to this proposal required that each country involved should prepare a complete dossier of its latest first-order triangulation giving the observed angles, astronomic positions, Laplace azimuths, and bases, together with any recommendations it might have as to the use of the data in the adjustment. This proposal by the Army Map Service was accepted by all the delegates at two lateral meetings held in Oslo in August, 1948, at the time of the Eighth General Assembly of the International Union of Geodesy and Geophysics. This action of the delegates was later confirmed officially by the Governments themselves. The Army Map Service pledged itself not to publish the results of the adjustment nor to release them to the International Asoociation unless and until the countries involved should indicate in writing their desire that this be done. It was agreed, however, that each country would be furnished the final adjusted data for the stations within that country. It was further agreed that the final geodetic positions of all astronomic stations to the nearest sexagesimal second of arc would be published for use in the study of the deflection of the vertical and the shape of the geoid.

Subsequent to the final act of concurrence at Oslo, the several countries immediately undertook the preparation of their data which, in some instances, involved considerable effort on their part. Four of these countries were requested to do some additional field work including an international connection by triangulation, base measurements, and Laplace azimuth observations. In other instances, certain countries have expedited necessary computations of their data in order to have them ready for the adjustment. It was suggested that the several nations forward their prepared data to the Central Bureau of the Association. This was done in nearly every case. Much credit is due Professor Tardi, the Secretary of the Central Bureau, and his staff, for the great effort expended and for the superb manner in which his office analyzed the accuracy and completeness of the numerous international connections, before transmittal of this large quantity of data to the Army Map Service. A considerable amount of travel and personal effort by the Secretary was necessary to clear up certain questionable boundary connections. All of this work by the Central Bureau is greatly facilitating the adjustment by insuring that the material, when received in Washington, was in excellent condition and factually correct.

It will be noted from Figure 1 that the Central European Adjustment, which was completed in 1947, reached the coast of Holland. The extension of the adjustment to include all of Western

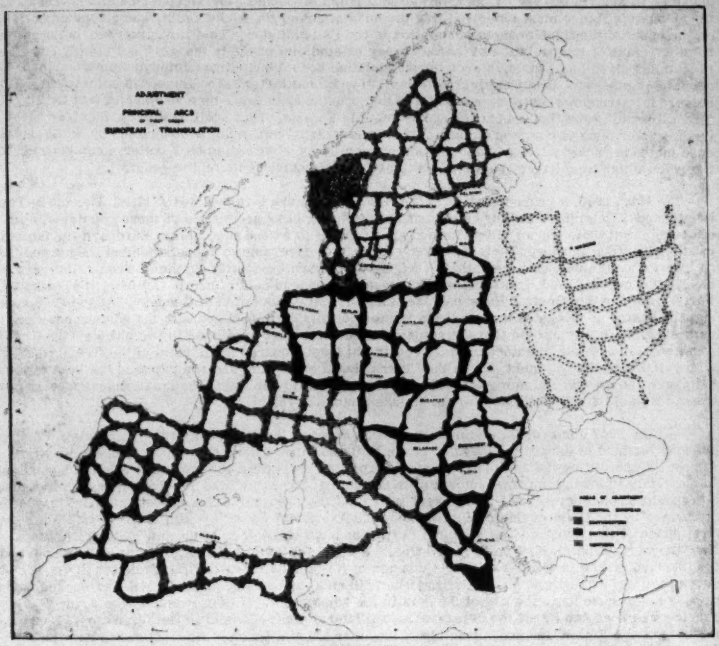


Fig. 1--Adjustment of principal arcs of the first-order European triangulation

Europe and a portion of Northwest Africa was, by that fact, separated into two blocks, called the Southwestern and Northern blocks. Owing to pressure of work at the Army Map Service, and by agreement with the Association, the Coast and Geodetic Survey was asked to undertake the extensive adjustment computations for Western Europe. This the Bureau agreed to do with funds transferred for that purpose.

The material for the Southwestern Block was transmitted by Army Map Service to the Coast and Geodetic Survey in the spring of 1949. The work has been prosecuted vigorously in the Division of Geodesy, headed by our retiring president, H. W. Hemple. Monthly reports have been issued by C. A. Whitten, who is in direct charge of the computations. The successful simultaneous solution of more than 2300 equations reflects much credit for ingenious planning and execution. The adjustment of the Southwestern Block is at this moment complete and the final listing of geographic positions is well along.

The entire data for the Northern Block is now in the hands of the Coast and Geodetic Survey. Preliminary operations are underway. It is anticipated that Whitten will be in a position to report to our meeting at this time next year that the Northern Block also has been brought to a successful completion.

We have discussed only the Central and Western areas of Europe. The adjustment of the first-order triangulation of Southeastern Europe which has been in process for thirty months was finished in January. To summarize, it will be evident from the above that the coming year should see the realization of the fond hopes of European geodesists, including those of that grand old man,

General Georges Perrier of France, namely, the mathematical adjustment of the first-order triangulation of Europe, all on a common geodetic datum and computed on the International Ellipsoid. Thus, we shall have in Europe not only a vehicle for the scientific study of geodesy but also a perfect basis for the cartography of an entire continent.

It is difficult to overemphasize the fact that the European Adjustment offers an unique example of international cooperation among the many sovereign nations of Western Europe. Our parent body, the International Association of Geodesy, may well take pride in its sponsorship of this scientific project which is nearing accomplishment in a most successful finale. The geodesists of Europe, on their own and without the intervention of any quasi-governmental body, have found a way to reach their objective through the simple means of voluntary cooperations. Those charged with the solution of international political and economic problems may well emulate the example set by these scientific men of goodwill.

Geodetic Division,
Army Map Service,
Corps of Engineers,
Washington 16, D. C.

(Manuscript received July 7, 1950; presented at the Thirty-First Annual Meeting, Washington, D. C., May 1, 1950; open for formal discussion until July 1, 1951.)

REPORT OF THE JESUIT SEISMOLOGICAL ASSOCIATION FOR 1949

J. B. Macelwane and R. R. Heinrich

The stations at Weston, Fordham, Georgetown, Buffalo, Cleveland, Cincinnati, Milwaukee, Chicago, Saint Louis, Florissant, Spring Hill, New Orleans, Denver, Santa Clara, and Spokane were in continuous operation during the year.

The new Sprengnether equipment at the University of San Francisco had not begun routine operation in 1949. The stations at Little Rock and Cape Girardeau resumed operations only in the Fall. New electromagnetic equipment was designed and built by Victor C. Stechschulte, at Xavier University, Cincinnati, and is giving good satisfaction. The station at Fordham University has been expanded to include tripartite installations for the study of two-second microseisms under a contract with ONR. Highly specialized electronic equipment is being used at the Florissant Station of St. Louis University for the study of half-second microseisms under an ONR contract.

Table 1--Annual number of preliminary bulletins and epicenters

Year	Number of preliminary bulletins	Number of epicenters
1944	48	53
1945	65	81
1946	62	94
1947	105	127
1948	139	158
1949	135	244

The triple contract between Science Service, the U. S. Coast and Geodetic Survey, and the Central Station of the Jesuit Seismological Association in Saint Louis has continued to bear fruit. But it has been greatly supplemented through the cooperation of the Department of State, the United States Navy, and other organizations, and especially by two way teletype service. The net result is an enormous increase in the amount of data available and in the number of epicenters that can be determined. Moderate shocks in out-of-the-way parts of the world and small shocks in many regions thus become amenable to eventual treatment. Table 1 illustrates this large rise in the number of determined epicenters. Table 2 lists the epicenters for 1949.

Table 2--Jesuit Seismological Association epicenters for 1949

Bulletin	Date	Origin	Epicenter		Depth	Remarks[a]
			Latitude	Longitude		
	1949	h m s	°	°	km	
1	January 9	07 48 11	6.5 N	81.5 W		T
2	January 13	08 47 38	24.7 S	179.3 E	650 ±	T
3	January 16	04 43 42	40.1 S	91.0 W		R
4	January 24	09 15 51	22.0 S	179.3 W	150 ±	T
5	January 27	07 18 10	4.0 S	151.7 E		T
6	January 27	11 00 13	53.1 N	162.3 E	150 ±	T
7	January 28	09 13 12	33.3 N	44.5 W	?	R
8	January 2	08 49 57	25 N	147 E	100 ±	R
9	January 9	10 34 54	22 S	66 W	250 ±	R
9	January 20	06 [illegible]	7 S	96 E	300 ±	R
9	January 25	07 53 08	11.5 N	84 W		T
9	January 27	07 18 10	4.0 S	151.7 E		R
9	February 2	17 41 34	52.7 N	173.2 W	300 ±	T
10	February 10	21 56 45	13.0 S	178.3 W		R
11	February 11	21 00 33	27.0 N	117.7 W		T
13	February 13	10 34 38	23.3 S	179.3 W	150 ±	R
13	February 14	18 07 35	17.3 N	104.5 W		T
14	February 15	08 09 00	19.5 N	70.0 W		T
15	February 15	09 01 38	19.5 N	70.0 W		T
16	February 23	16 08 03	40.0 N	24.5 E		R
17	February 27	00 13 00	9 S	27 W	?	R
18	February 1	10 15 36	4.5 S	138.0 E		R
18	February 5	20 15 20	19 N	73 W		R
18	February 11	07 30 50	6 S	108.5 W		R
18	February 23	03 32 20	17.9 N	104.5 W		R
19	February 21	11 38 07	9.0 N	40.0 W	80 ±	R
19	March 2	06 34 24	71.1 N	1.8 W		R
20	March 4	10 19 25	20.7 N	70.2 E	250 ±	T
21	March 9	13 38 37	27.0 N	117.3 W		T
22	March 13	18 43 15	30.1 S	67.5 W	150 ±	T
23	March 16	22 15 12	8.3 S	151.3 E	50 ±	T
24	March 17	21 06 13	8.2 S	151.3 E	50 ±	T
25	March 24	20 56 58	41.9 N	134.0 W		T
26	March 27	06 34 10	3.7 N	126.9 E		R
27	March 30	14 47 07	18.6 S	178 W	100 ±	R
28	March 4	01 17 13	6 S	102 E	150 ±	R
28	March 13	19 38 14	56.5 N	143.8 W		R
28	March 23	09 26 18	19 N	70 W		R
29	March 26	02 25 00	25.5 N	109.9 W		R
29	April 5	08 27 00	40.8 N	130.8 E	300 ±	T
30	April 13	15 13 00	10.8 N	41.5 W		T
31	April 13	19 55 30	47.2 N	122.5 W		T
32	April 19	21 34 34	15.3 S	174.5 W	100 ±	R
33	April 19	13 19 34	49.8 N	154.8 E	60 ±	R
34	April 20	03 39 10	38.0 S	73.1 W	100 ±	T
35	April 23	11 15 26	8.0 N	126.5 E	60 ±	R
36	April 24	04 22 19	28 N	55.5 E	100 ±	R
37	April 25	13 55 02	30.0 S	69.7 W	100 ±	T
38	April 30	01 23 27	6.2 N	126.0 E	100 ±	R
39	April 9	04 30 15	7.0 N	82.1 W		R
39	April 10	23 48 30	36.0 S	175.0 W		R
39	April 17	00 42 06	31 S	67 W		R
39	April 22	17 17 30	38.3 S	113.5 W	100 ±	R
40	May 3	05 56 55	49.8 N	154.3 E	150 ±	T
41	May 8	21 54 37	13.2 S	68.7 W	150 ±	T
42	May 9	13 36 30	4 N	94 E	100 ±	R
43	May 10	00 34 38	18.3 N	108.4 W		T
44	May 10	03 13 04	18.8 N	107.7 W		R
45	May 17	02 30 04	40.4 N	150.3 E	75 ±	T
46	May 21	21 40 11	37.2 N	141.5 E	50 ±	T
47	May 23	04 17 36	30.0 S	178.0 W	75 ±	T
48	May 24	13 49 39	17.2 N	108.9 W		T
48	May 24	16 20 08	17.2 N	108.9 W		T
49	May 25	04 24 00	43.0 N	83.0 W	100 ±	T
50	May 30	01 23 54	20.5 S	68.3 W	150 ±	T
51	May 2	11 25 49	33.9 N	115.2 W[b]		T
51	May 3	10 54 15	51.3 N	160.2 E		R
51	May 6	14 30 34	54.1 N	110.4 E		R
51	May 7	15 09 00	30.7 S	70.3 W	?	R
51	May 12	10 10 41	5.5 N	97.1 E		T
51	May 13	20 14 05	40.7 N	32.8 E		T
51	May 15	08 27 36	7.5 S	150.2 E		R
51	May 18	04 33 22	10.0 S	130.8 E		R
51	May 20	08 12 43	19.4 S	174.8 W	300 ±	R
51	May 24	18 59 30	37.1 N	142.0 E		T
51	May 26	06 23 12	33.3 N	33.3 W		R

[a] R indicates regional location; T indicates tentative coordinates. [b] Near Pasadena

(continued)

Bulletin	Date	Origin	Epicenter		Depth	Remarks[a]
	1949	h m s	Latitude °	Longitude °	km	
51	May 27	10 59 30	15.5 S	173.0 W		R
53	June 9	21 18 40	16 S	173 W	?	R
53	June 11	07 34 50	12.2 N	87.4 W	100 ±	T
54	June 12	17 52 27	27.5 S	63.1 W	600 ±	R
54	June 12	17 55 54	27.5 S	63.1 W	600 ±	R
55	June 15	05 47 23	51.5 N	179.4 W		R
56	June 19	22 04 31	61.2 N	148.1 W	50 ±	T
57	June 23	01 27 15	20.5 S	171.0 E	200 ±	R
58	June 24	22 39 01	7.8 S	104.4 E	200 ±	R
59	June 26	20 06 24	34.4 N	45.9 W		T
60	June 7	05 24 30	27 N	104 E		R
60	June 9	04 37 06	49 N	149 E		R
60	June 12	04 31 00	51 N	88.8 W		T
60	June 13	01 58 35	27 S	94 W	600	USCGS
60	June 17	01 35 00	1 S	13 W		R
60	June 17	04 20 36	36.4 S	39.4 E		T
60	June 19	13 24 25	34.7 N	45 W		R
60	June 23	13 08 54	18.3 N	68.8 W		R
60	June 25	19 17 10	20	175.0 W		R
60	June 26	05 42 25	36.8 N	30.2 E		T
60	June 26	08 41 25	0 N	125.5 E	?	R
60	June 26	20 01 50	18 S	167 E		R
61	July 3	11 27 48	50.7 S	163.7 E		R
62	July 3	09 19 02	18.1 N	145.2 E	100 ±	T
63	July 4	03 40 32	35.4 N	58.2 E		R
64	July 7	04 32 18	36.3 N	35.7 W		R
65	July 8	12 40 31	14.5 S	91.8 W	?	T
66	July 9	18 44 50	32.9 N	70.9 W		T
67	July 10	03 53 40	39.0 N	70.0 E		T
67	July 10	10 39 07	39.0 N	70.0 E		T
67	July 10	11 57 54	39.0 N	70.0 E		T
67	July 10	14 13 29	39.0 N	70.0 E		T
67	July 10	15 19 02	39.0 N	70.0 E		T
67	July 10	15 48 31	39.0 N	70.0 E		T
67	July 10	18 34 04	39.0 N	70.0 E		T
68	July 11	19 18 31	43.5 N	132.1 E	75 ±	R
69	July 18	04 43 18	6.8 N	134.4 E	150 ±	R
70	July 21	08 01 49	14.3 S	72.1 W	150 ±	R
71	July 23	10 39 07	53.5 N	169.4 E	150 ±	T
72	July 23	15 03 33	36.5 N	39.1 E		R
73	July 25	21 34 39	34.9 S	113.9 W		R
74	July 27	15 11 38	18.0 S	178.2 W		R
75	July 1	03 27 14	20.7 S	68.0 W	200 ±	T
75	July 3	21 06 02	13	73 W		R
75	July 4	13 47 53	30 S	173 W		R
75	July 8	18 18 10	71.8 N	[illegible] E		R
75	July 13	09 59 11	12.5 S	79.3 W		R
75	July 13	10 14 02	39.0 N	70.0 E		T
75	July 14	11 10 03	44.0 N	30.0 E		R
75	July 14	23 21 54	44.0 N	147.2 E	450 ±	R
75	July 16	09 57 31	13.9 N	92.5 W	?	R
75	July 16	00 23 54	1.2 N	125.2 E		R
75	July 19	09 43 58	17 N	100 W		R
75	July 20	22 20 09	10.7 S	161.9 E		R
75	July 25	03 50 20	17.4 N	145.5 E	?	R
75	July 28	07 04 30	16 S	75 W		R
76	August 1	08 03 40	18.5 S	96.3 W		R
77	August 5	19 08 14	0.3 N	79.3 W	?	T
77	August 5	19 08 53	0.3 S	79.3 W	?	T
78	August 6	00 35 39	19.3 S	174.8 W	100 ±	R
78	August 8	14 10 27	14.8 N	93.5 W		T
79	August 11	13 49 51	14.6 N	93.5 W		T
80	August 13	18 34 54	0.3 N	148.1 E		T
81	August 17	18 34 15	43.0 N	145.4 E	100 ±	T
82	August 17	18 44 10	30.3 N	41.1 E		T
83	August 18	13 33 32	9.2 N	82.9 W		T
84	August 22	04 01 13	53.7 N	153.2 W		T
85	August 23	19 43 40	52.5 N	130.9 W		R
86	August 23	20 34 42	52.6 N	129.5 W		R
87	August 25	14 14 22	52.6 N	130 W		T
88	August 7	08 15 34	50.8 N	128.7 W		R
88	August 8	07 08 12	19.0 S	69.2 E		R
88	August 8	19 07 36	19.0 S	74.7 W		R
88	August 11	14 40 34	44.5 N	39.5 W		R
88	August 14	22 22 22	14.4 N	92.5 W		R
88	August 24	08 07 16	43.5 N	127.1 W		R
88	August 24	09 22 00	9.5 S	108.9 W		R
88	August 24	10 37 26	52.4 N	153.2 W		R
88	Aug. 5	16 13 35	18.8 S	70.8 W	125 ±	R
89	August 25	22 25 57	6.8 S	130.5 E	300 ±	R
89	August 26	08 27 27	56.1 N	153.2 W		R
90	August 26	22 39 45	54.3 N	134.7 W		R
90	August 31	13 47 06	61.0 N	150.8 W		R
90	September 1	19 58 30	20 S	70.2 W		R

Bulletin	Date	Origin	Epicenter		Depth	Remarks[a]
	1949	h m s	Latitude °	Longitude °	km	
90	September 5	02 54 06	16.5 N	122 E		R
91	September 12	09 17 06	23.5 S	179.5 E		R
92	September 14	19 50 29	1.3 N	127.0 E		R
93	September 20	11 55 28	30.5 S	177.8 W	75 ±	T
94	September 21	04 15 15	10.0 N	84.5 W	100 ±	R
95	September 21	18 19 45	15.8 S	173.4 W		R
96	September 24	04 17 40	6.2 S	153.3 E	?	R
96	September 24	05 15 00	6.2 S	153.3 E	?	R
96	September 25	15 57 33	6.2 S	153.3 E	?	R
96	September 26	03 05 13	6.2 S	153.3 E	?	R
96	September 26	09 04 14	6.2 S	153.3 E	?	R
96	September 26	22 32 02	6.2 S	153.3 E	?	R
97	September 27	15 30 47	60.3 N	147.9 W	?	R
98	September 30	03 58 34	22.1 N	177.2 W		R
98	September 30	04 09 46	22.1 S	177.2 W		R
98	September 30	13 19 16	22.1 S	177.2 W		R
98	September 30	22 07 00	22.3 S	177.2 W		R
99	September 1	13 58 18	30.3 S	97.4 W		R
99	September 1	23 30 50	62.3 N	148.9 W	125 ±	T
99	September 5	03 18 13	17.0 N	121.2 E		R
99	September 8	02 47 05	47.8 N	153.5 E	75 ±	R
99	September 15	01 01 01	19.2 S	70.4 W		R
99	September 16	19 11 12	0.8 N	126.7 E	50 ±	R
99	September 18	13 45 58	14.3 S	68.9 W	100 ±	R
99	September 22	10 19 19	41.7 N	142.0 E	?	R
99	September 23	08 12 05	44 N	126.5 E	400 ±	R
100	October 4	10 20 30	1.3 S	21.8 W		T
101	October 7	12 02 30	33.7 S	98.4 E	100 ±	R
102	October 19	21 00 38	5.5 S	154.1 E	125 ±	R
103	October 20	12 45 05	9.2 S	153.9 E	100 ±	R
104	October 21	00 24 10	9.2 S	153.9 E	75 ±	R
105	October 23	05 12 30	9.1 S	145.0 E	150 ±	R
106	October 27	02 02 10	23.8 S	179.4 E		R
107	October 27	16 36 10	50.1 N	156.4 E		R
108	October 28	00 12 14	34.5 N	142 E		R
109	October 30	16 26 16	8.0 S	153.0 E		R
110	October 30	18 48 00	20.1 S	170.2 W	450 ±	R
111	October 29	06 31 56	9.8 S	160.3 E		R
112	October 31	01 39 34	50.1 N	155.3 W		T
113	October 31	17 55 42	5 S	154 E	100 ±	T
114	October 3	23 51 50	54 N	158 W		R
114	October 4	09 58 30	30 S	71 W		R
114	October 9	19 07 04	8.0 S	154.5 E		R
114	October 11	09 06 30	43.1 N	143.1 E	100 ±	R
114	October 13	03 35 30	19.8 S	169.5 E		R
114	October 13	12 47 35	17.8 N	99.8 W		R
114	October 17	08 00 30	30 S	71 W		R
114	October 21	03 32 30	53.3 S	148.0 W		R
114	October 26	00 02 37	10.3 N	41.7 W		R
114	October 27	04 34 16	29.9 N	113.0 W		R
114	October 31	07 44 05	44.3 S	168.2 E		R
115	November 3	01 12 47	48.5 N	154.4 E	100 ±	T
116	November 4	20 42 38	34.5 N	117.2 W		T
117	November 7	05 39 47	14.0 S	168.7 E	75 ±	T
118	November 10	04 42 38	11.0 N	86.0 W	50 ±	T
119	November 20	04 44 05	9.8 S	73.7 W		R
120	November 30	07 09 43	39.1 N	112.8 W		T
121	November 22	00 51 32	29.7 S	178.4 W	150 ±	R
122	November 27	08 42 39	17.5 S	174.1 W	100 ±	R
123	November 2	02 32 32	3.0 S	138.5 E		R
123	November 6	04 36 23	21.9 N	117.1 W		R
123	November 11	07 39 37	9.7 S	108.7 W		R
123	November 11	18 59 25	14.0 N	94.3 W		R
123	November 23	08 14 40	19.4 N	78.2 W		R
123	November 30	08 14 30	16.0 N	94.8 W		R
124	December 17	08 53 30	53.3 S	71.1 W		T
125	December 17	15 07 36	53.5 S	72.3 W		R
126	December 18	05 39 08	38.3 S	179.4 W	300 ±	R
127	December 21	13 31 29	19.0 N	67.3 W	100 ±	R
128	December 21	19 33 10	18.7 N	63.0 W	600 ±	T
129	December 22	09 30 50	15.9 N	93.0 W	100 ±	T
130	December 26	23 17 34	36.7 N	139.8 E		T
130	December 26	23 24 57	36.7 N	139.8 E		T
131	December 26	06 23 54	19.8 S	180		T
132	December 27	23 57 15	59.7 S	20.3 W		R
133	December 29	09 05 50	17.8 N	117.2 W		T
134	December 29	19 43 01	36.5 S	177.2 W	300 ±	R
135	December 1	11 11 35	5.8 N	84.9 W		R
135	December 5	13 42 15	5.8 N	84.9 W		R
135	December 7	18 13 36	36.4 N	24.4 E		R
135	December 15	02 32 00	17.8 N	102.7 W		R
136	December 23	22 40 47	19.5 N	104.3 W		R
136	December 28	08 25 30	40.7 N	29.4 W		R
136	December 30	13 45 40	51.0 N	174.9 W		R

[a] h indicates regional location; T indicates tentative coordinates; USCGS indicates location by the U. S. Coast and Geodetic Survey.

Institute of Technology,
St. Louis University,
St. Louis 8, Missouri

(Manuscript received July 10, 1950; presented at the Thirty-First Annual Meeting, Washington, D. C., May 2, 1950; open for formal discussion until July 1, 1951.)

THE INSTITUTE OF OCEANOGRAPHY, UNIVERSITY OF BRITISH COLUMBIA

G. L. Pickard and W. M. Cameron

An Institute of Oceanography was established at the University of British Columbia in the fall of 1949. The Institute is undertaking to train students at the graduate level in the principles and techniques of the oceanographic sciences and to carry out fundamental research in oceanography. The Institute is not self-sufficient but is regarded as a body whose function it is to correlate the interests of the University Departments of Chemistry, Physics, and Zoology in the study of the sea. It is supported jointly by the University and by Canadian organizations including the Defense Research Board and the Joint Committee on Oceanography. The latter represents the interests of the Royal Canadian Navy, National Research Council, Fisheries Research Board, and the Hydrographic and Meteorological Services. The Institute is directed by a Committee of Oceanography, under the chairmanship of W. A. Clemens, on which are represented the cooperating Departments and supporting organizations. The present staff includes W. M. Cameron (Department of Zoology), G. L. Pickard (Department of Physics), and J. P. Tully (Pacific Oceanographic Group, Honorary Lecturer in Chemistry).

Introductory courses in physical, chemical, and biological oceanography were offered during the session 1949-1950. In 1950-1951 a comprehensive program of instruction in synoptic and dynamic oceanography, biological oceanography, and the chemistry of sea water will be offered for the training of students in the basic principles and experimental practices. It is intended that students entering the Institute should already have graduated in one of the basic sciences. The courses offered in oceanography, together with the completion of a minor research problem, will lead to the M. A. degree in the major field of physics, zoology, or chemistry. It will also be possible to proceed to the Ph. D. degree in the first two of these fields. In addition to training students who intend to specialize in one of the oceanographic sciences, the Institute will make its facilities available to those working in other fields which have marine applications, for example, the marine aspects of engineering.

Laboratories for normal chemical work and for the analysis of field data are situated at the University. Facilities for field work are available through the Pacific Naval Laboratory, Esquimalt, and the Pacific Oceanographic Group, Nanaimo, for which two research vessels are maintained by the Royal Canadian Navy. These are H.M.C.S. Cedarwood, a 165-ft vessel, and C.N.A.V. Ehkoli, 84-ft. Both are equipped for oceanographic investigations and are devoted entirely to such work. The Ehkoli is used primarily for coastal work while the Cedarwood is suitable both for coastal and for deep sea investigations.

The basic research problems with which the Institute will be concerned in the first place are those particularly appropriate to the coast of British Columbia. In the physical field these problems include the mixing of fresh water with sea water, and the allied problems of the mechanics of mixing in estuaries and restricted bodies of water and of the turbulence associated with tidal currents. The open ocean off British Columbia has been investigated only to a very limited extent as yet, and it is hoped that the Institute will be able to cooperate with the Pacific Oceanographic Group in deep sea investigations in this region of the North Pacific. The wide ranges of salinity and of concentration of plant nutrients in the inshore waters present important problems in the chemistry of seawater.

The coastal region shows a variety of ecological conditions for both marine plants and animals. The interrelations between populations of marine organisms, especially fish, and their environment offer problems of particular significance on the Pacific Coast of Canada.

Cameron is at present engaged in an analysis of data obtained by the Pacific Oceanographic Group in Chatham Sound in 1948. Chemical investigations of the phosphate variation in stored seawater and of the determination of radioactive elements are in progress. Pickard has been on the staff of the Defense Research Board for the session of 1949-1950, while on leave of absence from the University, and after spending the winter at Scripps Institution of Oceanography has visited other oceanographic laboratories including Woods Hole Oceanographic Institution and the Atlantic

Oceanographic Group at St. Andrews, New Brunswick.

The Institute and the Pacific Oceanographic Group are cooperating in a study of the oceanographic circulation and distribution of properties in the sea in the immediate vicinity of Vancouver and the Fraser River. A grant, by the National Research Council, to the Pacific Oceanographic Group has permitted an intensive study of this region. The Institute provides shore facilities for the survey group assigned to the project, and the staff of the Institute is available for consultation. The present intensive program has been precipitated by a request from the Vancouver and Districts Joint Sewerage and Drainage Board whose future program of expansion depends upon the capacity of the circulation in the vicinity of Vancouver to absorb the increasing amount of sewage discharged into the Strait of Georgia. The present short-term exploratory research program is designed to assist the Sewerage Board in their special problem. A large number of basic observations are being obtained. These will be available to the Institute for research into special problems of estuary flow.

University of British Columbia,
Vancouver, Canada

(Communicated manuscript received September 27, 1950;
open for formal discussion until July 1, 1951.)

DISCUSSION OF

"ATMOSPHERIC REFRACTION AT COLLEGE, ALASKA, DURING THE WINTER, 1947-1948" by PIERRE ST. AMAND and HAROLD CRONIN

[Trans., v. 31, pp. 161-164, 1950]

Arnold Court (312 Livingston Terrace, S. E., Washington 20, D. C.)--Refraction by the Earth's atmosphere of the light from celestial bodies is simple to explain qualitatively, but extremely difficult to treat quantitatively, as was shown by WILLIS [1941]. The statement cited by the authors from Humphreys, that the total refraction depends only on the initial angle of incidence and the speeds in the first and last media, applies only to monochromatic light traversing plane layers; for concentric spherical shells the problem is far more complex, as Humphreys went on to show.

Basically, any computation of the amount of refraction involves some assumption about the rate of decrease of air density with height, in which the all-important factor is the vertical temperature distribution, or lapse rate. This is particularly important for rays emanating a few degrees above the horizon; at higher altitudes, formulas based on almost any atmospheric model can be adjusted to agree with observed refractions. Various theories have used various lapse rates; almost all United States tables, including the 1885 Doolittle tables which the authors used as standard, are based on those of Bessel, whose development assumed a lapse rate of around 0.6° F per 1000 ft, decreasing very slightly with height.

The authors speculated about the possible effect of "several well-defined temperature inversions" above their point of observation, but did not analyze their data in terms of air temperatures, either at the ground or in the free air, although ample radiosonde data for Fairbanks are available. Questions as to the proper temperature and pressure to use in computing refraction on star sights made during the Antarctic winter led to an investigation [COURT, 1949] of the meteorological premises of the Besselian tables being used, and to the formulation of crude tentative rules for adapting such tables to observations where low surface temperatures and steep inversions prevail. Also discussed were the meteorological premises of two recent American refraction theories, by GARFINKEL [1944] and WILLIS [1941], both based on mean lapse rates given by Humphreys for 416 central European soundings made between 1900 and 1912; Willis' formula is used now by the United States Coast and Geodetic Survey [HOSKINSON and DUERKSEN, 1947]. Meteorological and other premises of many other refraction formulas have been discussed by DE VANNSAY DE BLAVOUS [1944].

While lack of the original data or a clear statement about the computations makes conclusions uncertain, it appears that the only significant differences between observed refractions at College and those calculated from Doolittle's Besselian tables were at observed altitudes of less than 4°, where the observed values were greater than the calculated. This is contrary to the general finding in cold regions where pronounced temperature inversions occur, since the mean lapse rate under such conditions is less than that assumed by the conventional corrections to tables.

In this case, however, all observations were made toward the south, sighting across the Tanana Valley and over the Alaska range, shown in the photographs of Figures 1 and 2. Perhaps the thermal stratification was not horizontal, but followed to some extent the surface configuration. Furthermore, the Sun's rays at the lowest altitudes observed must have almost grazed the mountain tops before reaching the observatory, so that some double refraction occurred which may account for the anomalous greater total refraction observed.

In an opposite climate, observed refractions at altitudes up to 12° recently were found [SMILEY, 1950] likewise to be significantly greater than those given by tables (except at 0°, where the value was uncertain). The 6252 observations were made in April, May, and June, 1947 on board ship in the western Atlantic between the tropics, and thus presumably in an equatorial air mass with lapse rate approaching the wet adiabatic. Here the temperature decreases with height more slowly than over London or Königsberg on summer evenings, conditions for which Bessel computed the temperature correction to his tables. However, just as at College, no attention

was given to the atmospheric structure in analyzing the observations, which are attributed to sea level with air and water temperature 80° F and pressure 30 inches.

No such qualification for temperature or pressure is given for the authors' "Suggested corrections to tables of refraction" (Table 2). These corrections are roughly the same as those in Doolittle's Besselian tables for a temperature of +25° F, and about one-third of those for -25° F (the basic table is for +50° F, 30 inches). Even if these corrections be insufficient, and the paper under discussion offers insufficient detail to be convincing, certainly any further correction must have some relation to ambient temperature. Thus it is difficult to agree with the authors' conclusion that use of their table will reduce the inaccuracy of position determinations from observations at low altitudes in the arctic. They are correct, however, in saying "a theoretical investigation of the problem should prove fruitful." Their paper would have been greatly enhanced by such an investigation of atmospheric refraction.

References

COURT, ARNOLD, Refractive temperature, J. Franklin Inst., v. 247, pp. 583-595, 1949.

DE VANNSAY DE BLAVOUS, P., On refraction and refraction tables, Hydrogr. Rev. (Intl. Hydrog. Bur., Monaco), v. 21, pp. 17-36, 1944.

GARFINKEL, BORIS, An investigation in the theory of astronomical refraction, Astron. J., v. 50, pp. 169-179, 1944.

HOSKINSON, ALBERT J., and J. A. DUERKSEN, Manual of geodetic astronomy, U. S. Coast and Geod. Surv., Spec. Pub. 237, Washington, 1947.

SMILEY, CHARLES H., Atmospheric refraction at low angular altitudes in the tropics, Navigation, v. 2, pp. 110-113, 1950.

WILLIS, JOHN E., A determination of astronomical refraction from physical data, Trans. Amer. Geophys. Union, v. 22, pp. 324-336, 1941.

W. D. Lambert (P. O. Box 687, Canaan, Connecticut) and F. W. Darling (45 Kenilworth Ave., Garrett Park, Maryland)--The problem of astronomical refraction is much less simple than might be inferred from the article of St. Amand and Cronin. It has engaged the attention of practical astronomers and of mathematicians from the 17th Century to the present. The most important recent contributions to a solution of the problem come from a better knowledge of the upper atmosphere. This discussion is an attempt to state succinctly, but without proof, some of the main results reached during the past three centuries and to clarify some of the statements in the article in question that might be open to misinterpretation. Not having ready access to original sources, the writers have drawn freely on the work of BRUHNS [1861]. Considerable assistance was given by members of the U. S. Coast and Geodetic Survey in the computation of the table.

St. Amand and Cronin state that their corrections apply to the refractions given in DOOLITTLE [1896]. Doolittle gives two methods of computing the refraction, both based on the work of BESSEL [1826].

The first gives a rough and ready method of computation. Bessel's mean refractions are given for barometric pressure of 30 inches, or 76.2 cm, and temperature of 50° F, or 10° C. Factors are given for reducing the mean refraction to other readings of the barometer and thermometer. These factors are based on the assumption that the refraction is directly proportional to the height of the mercury barometer reduced to standard temperature (nothing is said about standard gravity) and inversely proportional to the absolute temperature. This assumption, though not theoretically valid, is practically correct for moderate zenith distances but fails in increasing measure as the horizon is approached.

The second method gives merely Bessel's auxiliary tables for computing the refraction. If Bessel's factors A and λ, applicable respectively to the barometer and thermometer corrections, were each exactly unity, then the assumption made in connection with the first method would be correct. But near the horizon both of them, especially A, depart considerably from unity.

The article discussed is concerned with refractions near the horizon, but it is not stated which of Doolittle's two methods was used in computing the refractions to which corrections were determined by observation. The authors of the article determine by observation corrections both above and below a zenith distance of 85°. Observation, of course, rather than theory, should control, but perhaps it was not realized (for Doolittle does not mention it) that for zenith distances greater than 85° Bessel threw his mathematical theory overboard. Between 85° and 90° his

tables are based on observations by Argelander at Königsberg (Regiomontanae in the title of Bessel's work is the latinized form of Königsberg as an adjective in the nominative plural feminine) and must deserve at least the same confidence for Königsberg as those of St. Amand and Cronin do for College, Alaska.

All mathematical theories of refraction assume that the atmospheric strata of equal density, and hence of equal refractive index, are horizontal. A density gradient caused by differences in the weather in adjoining regions will disturb this assumed horizontality and cause small anomalous refractions, even at the zenith, and greater ones at greater zenith distances. Apart from anomalies of this sort, astronomical refractions may be divided into three ranges of zenith distances.

The first range is between 0° and say 74° of zenith distance z. In this range the refraction may be expressed as a power series in tan z.

$$R = a \tan z - b \tan^3 z + c \tan^5 z - d \tan^7 z \ldots \quad \ldots\ldots\ldots\ldots (1)$$

where R is the refraction, and a, b, c, d, ... , are constants for a given assumed relation between atmospheric density (or index of refraction) and height above the observer. Now for almost any reasonable assumptions in this regard the coefficients c, d, ... , are so small that for zenith distances less than 74° the corresponding terms may be neglected.

LAPLACE [1805], and (less explicitly) ORIANI [1788] before him, showed that the coefficients a and b are practically independent of the assumed constitution of the atmosphere and depend only on the density at the observer's station and on the barometric reading there. This appears numerically in Table 1, which gives, for the same index of refraction, temperature, and barometric pressure, the refractions for various zenith distances under three different assumptions as to the decrease in density of the atmosphere as the height above the observer increases. These assumptions bear the names of Cassini (1625-1712), Bouguer (1698-1758), and Newton (1642-1727). Bouguer's assumption is connected also with the names of the mathematician Simpson (1710-1761) and the astronomer Bradley (1693-1762). These assumptions [CASSINI, 1730; BOUGUER, 1739; HALLEY (Newton), 1721] give highly schematic and artificial distributions of density, quite different from any possible reality, and as between Bouguer and Newton in opposite directions, but within this region we may say that one assumption is as good as another, provided the strata be horizontal and that the density and hence index of refraction have the assigned values at the observer and that in outer space the density be zero and the index unity. Inversions of temperature with increasing elevation are not excluded. It is only within this region that the statement attributed to Humphreys is true, that refraction depends only on atmospheric conditions at the observer. It may be added that Laplace's investigation shows that, even in this region, the coefficients a and b of the first two terms of the refraction formula (1) do not vary together exactly in the same ratio when temperature and pressure are changed.

The second region may be taken to begin at zenith distance 74°, the limit specified by Laplace, and to extend only a little beyond 80°. Here almost any plausible theory will make the succeeding coefficients, c, d, ..., somewhat alike for different theories but with increasing differences in different theories for the remoter coefficients. Even for the rather implausible assumed distributions of density in the C, B, and N columns of Table 1, the refractions for 75°, 80°, and 82.5° do not greatly differ. It may be remarked also that the further out we go in the series, the less do the coefficients conform to the rule of changing in direct proportion to the barometric pressure and in inverse proportion to the absolute temperature.

The values of the coefficients do not decrease fast enough to make the series (1) convergent near the horizon, so that beyond a certain zenith distance some other method of computation must be employed. From 80° or 82° on, the three assumptions above give increasingly discrepant results. At the horizon the truth lies on the whole between assumptions B and N. This region from 80° or 82° to the horizon is the third region. No hard and fast theory is always good here. A precise calculation can be made only with a knowledge of the state of the atmosphere at those points through which the refracted ray passes.

Assumptions C, B, and N may be considered as approximate special cases of a more general assumption with an arbitrary parameter. Let h, ℓ, ρ, ρ_0, p, and p_0 have the meanings previously assigned, let T be the absolute temperature at elevation h above the observer's station, and let T_0 be the absolute temperature at the station. Further, let n be an arbitrary parameter. (See Eq. 3, bottom third of next page.)

Table 1 (with explanations)--Astronomical refraction according to the assumptions of Cassini (C), Bouguer (B), and Newton (N)

Zenith distance	Refraction					
	C		B		N	
°	′	″	′	″	′	″
65	2	09.2	2	09.2	2	09.2
70	2	45.0	2	45.0	2	45.1
75	3	42.6	3	42.7	3	42.7
80	5	31.9	5	32.1	5	32.4
82 1/2	7	13.3	7	14.0	7	15.2
85	10	10.0	10	13.8	10	19.9
87 1/2	15	45.0	16	23.3	17	09.8
90	21	32.1	30	22.0	39	53.7

Explanation of Table 1--Cassini (C) assumes a shell of atmosphere of uniform density equal to that at the observer's station up to the so-called "height of the homogenous atmosphere," about eight kilometers above sea level. At this height the density changes abruptly to zero, which is the density of outer space, and the index of refraction becomes and remains unity.

Bouguer (B) assumes that the index of refraction is connected with the distance from the Earth's center by the equation

$$a/r = (\mu/\mu_0)^m \quad \ldots\ldots\ldots (2)$$

Here a is the radius of the Earth (treated as a sphere) out to the observer's station, μ_0 the index of refraction there, r a greater radius, and μ the corresponding index. The exponent m for Table 1 is determined in a rather complicated way from μ_0 and ℓ, the height of the homogenous atmosphere. In Table 1 its value is 8.5194. The result of Bouguer's assumption is that the density diminishes very nearly in arithmetical progression with increasing height above the observer, reaching zero at a height approximately equal to 2ℓ. The formula for ℓ is

$$\ell = p_0/g_0\rho_0 = 8 \times 10^5 \text{ cm} = 8 \text{ km, roughly}$$

g_0, ρ_0, and p_0 being respectively gravity, air density, and air pressure at the observer, all quantities being expressed in cgs units.

Newton's (N) hypothesis assumes constant temperature and a density proportional to pressure. If we neglect the variation of gravity with height, the density decreases in geometrical progression as the height increases in arithmetical progression, that is,

$$\rho = \rho_0 e^{-h/\ell}$$

where ρ is the density at height h above the observer. The atmosphere is thus of indefinite extent.

Columns C, B, and N have all been computed with the data quoted by Bruhns: $\ell/a = 0.0012525$ (a = radius of Earth out to observer), and $\mu_0^2 = 1.000588094$. These are intended to apply at the observer's station to a temperature of 0° C = 32° F and a barometric pressure of 76 cm.

$$\left.\begin{aligned} \rho/\rho_0 &= [1 - h/(n+1)\ell]^n \\ p/p_0 &= [1 - h/(n+1)\ell]^{n+1} \\ T/T_0 &= 1 - h/(n+1)\ell \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots\ldots (3)$$

We see that these assumptions satisfy the conditions for a perfect gas, if the variation of gravity be neglected.

If we put n = 0, we have Cassini's assumption, a shell of uniform density ρ_0 and thickness ℓ. If we put n = 1, we get approximately Bouguer's assumption, that is, densities decreasing in arithmetical progression up to height 2ℓ, at which height the density is zero. The assumption n = ∞ gives Newton's constant temperature and a decrease of density according to the exponential law

$$\rho = \rho_0 e^{-h/\ell}$$

GARFINKEL [1944] found that the average horizontal refraction can be represented by a value of n between 4 and 6, but to represent values of the horizontal refraction that are sometimes observed requires values of n outside this range. Garfinkel's assumption is seen to mean a constant lapse rate of temperature and a limiting height of the atmosphere equal to $(n + 1)\ell$. This cannot be a very exact representation of actual conditions, but if n is so chosen as to represent the average

lapse rate in the lower atmosphere, where most of the refraction occurs, Garfinkel's theory, with the further refinements that he includes, gives an excellent representation of average refractions, even near the horizon.

It means the same thing mathematically but it gives an apparently narrower range to our variable parameter if we replace n by its reciprocal k = 1/n. Then we can state our results as follows. The average refraction is represented by taking k between unity (Bouguer) and zero (Newton); the practical range lies well within the limits k = 0.25 (n = 4) and k = 0.167 (n = 6). Garfinkel takes as a good average representation k = 0.2 (n = 5). His theory includes other refinements such as an allowance for the change of gravity with elevation, for the existence of the stratosphere, and for small variations from the adopted mean value of n = 5.

Geodesists encounter a kind of refraction that is even more troublesome than astronomical refraction near the horizon. This is the refraction of a ray between two points both on the surface of the Earth and hence both within its atmosphere. Astronomical refraction near the horizon is a limiting case of this and a complete theory of astronomical refraction should be applicable to geodetic refraction. Garfinkel extends his theory to include geodetic refraction.

The geodetic refraction has been found to vary with the time of day, the season of the year, the region of the globe, and the kind of terrain over which the refracted ray passes. There have been numerous theoretical investigations and numerous empirical rules. Statistically these investigations and these rules have doubtless improved computed values of the geodetic refraction but even an apparently high coefficient of correlation does not mean great certainty in prediction. The matter has rather dropped from sight in modern geodesy, because less use than formerly is being made of vertical angles to determine elevations. Those interested in the theory will find it, along with further references, in the works of HELMERT [1884] and WALTER [1898], especially the latter.

What has just been said about the uncertainties of geodetic refraction applies in lesser degree to astronomical refractions near the horizon. Tables of astronomical refraction in current use were made for use at fixed observatories, mostly near sea level. What has been done in the past for geodetic refraction could be done for astronomical refraction near the horizon, that is, empirical rules could be established showing how the refraction could be expected to vary with weather condition, the time of day, the season, the altitude, the terrain, and other factors.

The authors of the article discussed have made a beginning. The main point of this discussion is that a systematic correction of astronomical refractions is not a task to be undertaken lightly and unadvisedly and that to the best of rules there will be some exceptions caused by anomalous atmospheric conditions. The only certain way to get a correct and certain value of the refraction along a low-lying ray of light is to obtain, by one means or another, values for the temperature and pressure along the ray, as has been done occasionally for experimental purposes in connection with radar observations [KROLL, 1949]. But such an elaborate set-up would be impracticable for routine astronomical observations, or if not impracticable, unduly expensive.

In the bibliographical notes at the end of this discussion under the heading HALLEY [1721], it is noted that Newton computed his table by quadratures. This fact was emphasized by BIOT [1836], using letters of Newton then recently published. Biot in his opening remarks has this to say, freely translated: "Newton . . . . . deduced the numerical values of the refraction for the case of uniform temperature by making use of his method of approximate quadratures, a fact that long remained unknown. The usefulness of this method for problems of this sort has not up to now been sufficiently realized. As the methods of the infinitesimal calculus were developed, several of the great mathematicians who contributed to this development took up the problem of refraction, but they seemed to regard it rather as a problem in mathematics than as a problem of fitting their analysis to the physical data that they possessed, incomplete and inaccurate as these were."

How incomplete and inaccurate these data were, Biot himself probably scarcely realized, but his remarks about the usefulness of quadrature as a means of constructing tables of refraction are even more pertinent today than when he wrote. Our powerful mechanical and electronic computing machines could nowadays easily turn out refraction tables corresponding to any conceivable distribution of density and thus to different conditions of region, season of the year, altitude, and other variables, and in such numbers as to embarrass the observer by their very multiplicity rather than help him, especially since, except near the horizon, a fairly simple set of tables would serve well enough, except under abnormal atmospheric conditions.

References

BESSEL, F. W., Tabulae regiomontanae reductionum observationum astronomicarum ab anno 1750 usque ad annum 1850 computatae, Regiomonti Prussorum, 1826.

BIOT, JEAN BAPTISTE, Sur les réfractions astronomiques, Connaissance des Tems . . . . , 1839, pp. 3-114, published 1836.

BOUGUER, PIERRE, Sur les réfractions astronomiques dans la zone torride, Mémoires de Paris, 1739.

BRUHNS, C., Die astronomische Strahlenbrechung in ihrer historischen Entwickelung, Leipzig, 182 pp., 1861.

CASSINI, GIOVANNI DOMENICO, Table des réfractions et des parallaxes du Soleil, Mémoires de l'Académie Royale des Sciences, depuis 1666 jusqu'à 1699, Paris, v. 8, p. 81, 1730.

DOOLITTLE, C. L., A treatise on practical astronomy as applied to geodesy and navigation, 4th and revised edition, New York and London, 1896.

GARFINKEL, BORIS, An investigation in the theory of astronomical refraction, Astron. J., no. 1148, pp. 169-179, 1944.

HALLEY, EDMUND, Some remarks on the allowances to be made on astronomical observations for the refraction of the air, Phil. Trans., v. 31, pp. 517-519, 1721. (Newton's theory is inferred from the table published by Halley on refraction. It is now known that Newton reached his numerical results by quadratures. The full mathematical theory involved mathematical developments rather in advance of his time. The necessary analysis was given later by Kramp, Analyse des réfractions astronomiques, Strasbourg, 1799, and used in substance by Bessel with altered numerical constants. The Kramp-Bessel formula used in computing column N of the table was corrected by including the effect of the small omitted term noted by OPPOLZER [1878].)

HELMERT, F. R., Die mathematischen und physikalischen Theorieen der höheren Geodäsie, v. 2, Chap. 8, Leipzig, 1884.

KROLL, CEDRIC W., A rigorous method for computing geodetic distance from shoran observations, Trans. Amer. Geophys. Union, v. 30, no. 1, pp. 1-4, 1949.

LAPLACE, P. S., Traité de mécanique céleste, v. 4, 1805.

OPPOLZER, TH., Eine Bemerkung über die Berechnung der Refraction, Astron. Nachr., v. 92, p. 30, 1878.

ORIANI, BARNABA, De refractionibus astronomicis, Effemeridi di Milano, 1788.

WALTER, ALOIS, Theorie der atmosphärischen Strahlenbrechung, 74 pp., Leipzig, Teubner, 1898.

Other treatments on refraction published after Bruhns' work and especially worth consulting are:

GYLDÉN, J. A. H., Constitution der Atmosphäre und Strahlenbrechung, Russian Acad. Sci., St. Petersburg, v. 10 and 12, 140 pp., 1867 and 1869.

HARZER, PAUL H., Untersuchung über die astronomische Strahlenbrechung auf Grund der Differentialgleichungen der elastischen Lichtbewegungen in der Atmosphäre, Astron. Nachr., v. 104, pp. 65-78; v. 107, pp. 145-194, 1883; v. 146, pp. 377-424, 1898.

NEWCOMB, S., A compendium of spherical astronomy, London, Chap. 8, 1906.

OPPOLZER, TH., Vorläufige Mitteilung über eine neue Refractions-formel, Astron. Nachr., v. 89, pp. 365-367, 1877.

RADAU, RODOLPHE, Théorie des réfractions astronomiques, Annales de l'Observatoire de Paris, v. 16, 114 pp., 1882.

Pierre St. Amand (2050 Emporer Ave., Temple City, California, Author's closure)--The authors are indebted to Lambert and Darling for the excellent discussion of the subject paper and for their illuminating discourse on the theories of atmospheric refraction in general.

It is interesting to note that, assuming temperature and pressure corrections to be reasonably correct, the observations at altitudes less than five degrees indicate the difference between refraction observed at Königsberg and that observed at College, some 125 years later.

While, as Lambert and Darling point out, it would be impractical to construct enough tables for use at each locality on the Earth to cover all the possible combinations of the many variables affecting the refraction, it is necessary to realize that the blind use of any one table, say the Königsberg table, could only result in error when used under conditions markedly different from those for which the table was constructed. It would be possible to construct auxiliary tables to cover greater zenith distances, for use in localities such as the Arctic, where it is necessary to observe

the low-lying Sun for navigational purposes.

To look at the matter from a different standpoint, observations of refraction near the horizon might be used to gain information about the structure of the atmosphere. However, the mathematical operation would be bothersome and perhaps not worth the effort.

The authors agree that the systematic correction of atmospheric refraction tables is not a task to be undertaken lightly and unadvisedly and again point out that the corrections suggested are only a first attempt.

Several points of Court's criticism should be clarified. (1) The observations were corrected for ground temperature and pressure. The "ample radiosonde data for Fairbanks" were investigated and it was found that observations were made only in the morning and evening. The refraction was measured at noon. However, an attempt was made to use the temperature, pressure, and radiosonde data, but no significant results could be detected in the available time. (2) The method of reduction is clearly stated in the subject paper. (3) Court gives no evidence to support his assertion that our results are contrary to general findings in cold climates. (4) The rays of the Sun did closely approach the mountain peaks on some of the lower observations, but how this could result in double refraction is not at all clear.

The data and the conclusions are clearly labelled as preliminary. They were, in fact, of an exploratory nature, and this investigation was conducted to determine whether or not an elaborate investigation would be justified. The results indicate that further investigation is desirable. These observations were made with all due care and the authors feel that the basic data are accurate.

LETTERS TO THE EDITOR

PROTONS AND THE AURORA

On September 30, 1950, an auroral arc over Arnprior, Ontario, was observed by means of spectrograms obtained there and simultaneously at Ithaca, New York, 330 km away. The Arnprior spectrograph was aimed nearly along the lines of magnetic force while the Ithaca spectrograph was aimed northward at right angles to the field. Both were pointed toward the same part of the arc.

Both exposures clearly show the hydrogen line at 6563A. On the Ithaca plate it is centered on 6562A but broadened in both directions by about 10A. The Arnprior spectrum shows the broadening of about 10A to red but the violet broadening extends to about 6530A. The center of the line is thus shifted about 15A, the maximum violet shift being at least 30A.

Thus, the hydrogen is in motion toward the Earth with a mean velocity of 675 km/sec and maximum velocity of 1350 km/sec. Since all our previous spectra, including those aimed low in the east, show only a broadened hydrogen line, while the Arnprior picture shows the violet shift, we must conclude that the hydrogen is coming in from outside in the form of protons.

The broadening on the Ithaca spectrum is due to line-of-sight motion of the scattered atoms, or to helical motion around the lines of force.

These results were obtained during a moderate aurora, whereas a velocity of 3200 km/sec was obtained by Meinel during the great aurora of August 18-20, 1950. This suggests a relation between size of the aurora and energy of the protons.

The hydrogen radiations characterizing the aurora are, therefore, of great geophysical interest. It is suggested that fast spectrographs be aimed at the corona center whenever possible, but useful results can be obtained even when aimed 45° away. The hydrogen line appears much stronger than the nitrogen positive bands during the rising phase of a display.

This research was supported in part by the National Geographic Society and by the U. S. Signal Corps under contract W36-039-SC-44518.

Cornell University,
Ithaca, New York

C. W. Gartlein

Transactions, American Geophysical Union Volume 32, Number 1 February 1951

LETTERS TO THE EDITOR

ESTIMATING BED LOAD

Included in the large number of problems confronting the hydraulic engineer there is that of estimating the rate at which a reservoir will fill with sediment. To accomplish this task it is necessary to determine the total volume of sediment carried by a stream. Measurements of the sediment load of numerous streams in this country have been made which are invaluable in estimating the total sediment load carried by these streams; however, the instruments used to obtain a sample of sediment carried by the stream can accurately measure only a part of this load. It is customary, therefore, to estimate the unmeasured amount and to add it to the measured amount to obtain the total sediment load. For reasons which will be explained later, this unmeasured amount which is added to the measured load is frequently called the "bed load."

With the instruments and methods in use at present, samples usually are taken of only the suspended material in the stream. The sampling, however, does not include the suspended material transported by the stream over the entire stream depth since the construction of all samplers in general use at this time is such that the nozzle of the sampler remains a definite distance above the stream bed when the base of the sampler is resting on the stream bottom. Consequently, the nozzle of the sampler travels only from the surface of the stream to a definite distance above the stream bed. This distance is about 0.3 ft when measurements are made with the standard samplers in current use in this country. The sample is assumed to be typical of the entire sediment discharge above this distance from the stream bed. The assumption made in the above discussion is that the samples are taken by the depth integration method which averages the concentration for the depth sampled and which is the method now very widely used. It can be readily seen that the error in sampling will increase as the proportion of the total depth of unsampled flow increases. The factor of the depth of flow also has an important bearing on this error since a given unsampled distance produces a greater proportion of the total depth of flow in a shallow stream than in a deep stream; therefore, shallow streams produce greater errors from a given unsampled depth than deep ones. The effect of this correction in very shallow streams may be surprisingly large.

The difference between the total load and the load measured with the conventional suspended-load instrument, therefore, consists of two parts: (1) the contact load which is the coarse material which rolls or slides along the bed of the stream; and (2) a part which results from the fact that because of heavy concentrations of the coarser suspended sediments which pass below the lowest sampling level the average concentration of suspended load determined by the instrument is less than the actual average concentration. Since both of these factors result from the coarser material traveling on or close to the bed of the stream, the difference between the total load and the load obtained by the conventional suspended-load sampler is called the bed load.

Methods of computing bed load--There are two methods that may be used for computing the bed load of a stream. (1) The first method requires that a suspended sediment sampling station be located at the head of a reservoir which can sample practically all of the runoff into the reservoir. It is also necessary that the water passing through the dam be sampled or that the trap efficiency of the reservoir be estimated. It is then possible by using these data and the data obtained by reservoir surveys to compute the bed load as it is the difference between the sediment determined by the surveys and that which passes the sediment sampling stations at the dam and above the reservoir. Frequently, however, it is found that the error which may be incurred in converting the volume of sediment determined by reservoir surveys to weight so that it can be compared to the weight of sediment that passed the sediment sampling station is about equal to the bed load. (2) The second method requires the use of the bed-load formulas. The total non-suspended load can be computed by formulas developed by Kalinske, Einstein, Straub, and Meyer-Peter, and Muller. Practically all of the so-called bed-load formulas, with the exception of Schoklitsch's which was developed for coarser materials on European streams and was verified by measurements on these streams, make use of the laboratory traction flume studies by Gilbert, Kramer, U. S. Waterways Experiment Station, and others. These studies were for the purpose of determining the

quantity of bed-load transport, and all materials transported were considered as bed load, whereas actually, especially at the higher flows and with the finer materials, some of the material was transported in suspension. The bed load, because of the non-uniform distribution of sediment in the vertical, previously described, may be computed by means of the method described in the Analytical Study of Methods of Sampling Suspended Sediment, Report No. 3. Because of the lack of accurate experimental data to check the various formulas involved, it is not possible at this time to appraise the accuracy of bed-load estimates computed by either method.

Methods of estimating bed load--The usual method of determining the amount of bed-load correction is to assume that it is a certain per cent of the load determined from the suspended-load sediment samples. The percentages which have been used in the past have been based on judgment, which in many cases has been little better than a guess. Opinions differ considerably on the correct value of this percentage to assume. For different streams, percentages which have been used by various engineers range from zero to 100 per cent; and it is probable that the correct value for these streams covers a range of at least this magnitude. Very few quantitative measurements of the total load have been made to serve as a guide in making accurate estimates of bed load; but there are certain general relations which, if kept in mind, will greatly narrow the limit of error which an engineer is likely to make in estimating the bed load. There are three major variables which affect the amount of bed load a stream may carry. They are as follows: (1) size of bed material or the fall velocity of the particles; (2) slope of the stream or the average stream velocity; and (3) nature of the channel including the depth, size, shape, and roughness of its bed and banks.

Minor factors include temperature and the effect of ice. To aid in the evaluation of the effect which these variables have on the bed load, the following criteria are set forth: (1) The smaller the actual concentration of suspended material, the higher usually will be the per cent of bed load. This is a very important factor in estimating bed load. (2) The smaller the difference in the particle sizes of the bed-load material and the suspended-load material, the higher will be the percentage of bed load to the total load. (3) The ratio of bed load to suspended load is apt to be larger for low or medium stages than it is for high stages. Thus, a stream in which the flow does not fluctuate widely, is likely to carry a larger per cent of bed load. This criterion does not necessarily apply to very steep mountain streams which move boulders at flood stage. In such streams, the bed-load ratio may increase with an increase in discharge. (4) Streams with wide, shallow channels carry a higher proportion of sediment as bed load than streams with deep narrow channels. (5) Stream channels with a high degree of turbulence tend to have smaller amount of bed load.

A clue to the magnitude of the bed-load correction can often be found in the nature of the source of the sediments involved. The three common types of erosion which produce sediment are (1) sheet erosion, (2) gully erosion, and (3) bank cutting. Sediment produced by sheet erosion tends to be fine; and, therefore, streams carrying sediment derived from this source tend to have a small amount of bed load. However, if the top soil is predominately sandy and the drainage-ways are comparatively small, then shallow sheet erosion may produce considerable bed load. Gully erosion and bank cutting are likely to produce coarser material and, therefore, more bed load than is obtained from sheet erosion. However, if the material below the surface layer of the ground is fine or is composed of material which breaks down into fine material, as does shale, gully erosion or bank cutting do not produce a large amount of bed load. Since bed load is composed of the coarser particles, in order to have an appreciable amount of bed load, these coarser particles must be found in abundance on the watershed and must be so located that they can be easily moved into the drainage-ways of the stream's channel system.

For some purposes it is desirable to estimate the bed-load movement as a given time, and for others it is necessary to estimate the average movement over a period of years. Most of the conditions previously discussed deal more particularly with the conditions at a given time. When the average bed load over a period of time is concerned, the flow variability must be considered. Most of the sediment load of streams is carried during high-flow periods since at these times both the discharge and the sediment concentration are high. At times of high flow, however, the depth of flow and turbulence are greater and tend to lower the bed-load content of the stream (at least in the case of the sand sizes, the amount of which is likely to be of greater magnitude than the coarser material). The bed-load correction in times of high flow is, therefore, likely to be a smaller part of the suspended load than in times of low flow; consequently, with a more variable flow the bed-load correction will be smaller when expressed as a per cent of the total quantity of measured suspended load for the period of flow involved.

Table 1--Maddock's classification for determining bed load

Concentration of suspended load	Type of material forming the channel of the stream	Texture of suspended material	Per cent bed load in terms of measured suspended load
ppm			pct
Less than 1000	Sand	Similar to bed material	25 to 150
Less than 1000	Gravel, rock, or consolidated clay	Small amount of sand	5 to 12
1000 to 7500	Sand	Similar to bed material	10 to 35
1000 to 7500	Gravel, rock, or consolidated clay	25 per cent sand or less	5 to 12
Over 7500	Sand	Similar to bed material	5 to 15
Over 7500	Gravel, rock, or consolidated clay	25 per cent sand or less	2 to 8

From the foregoing discussion it can be seen that a great many factors are involved in the estimation of bed load and that it is difficult, if not practically impossible, to draw up a simple rule or formula which will give quantitative answers to all cases. Probably the best answer to the problem devised to date is that suggested by Thomas Maddock, Jr. and given in Table 1. This table takes into account only a portion of the variables previously mentioned, but those omitted can be given consideration in determining that part of the suggested bed-load range to adopt.

U. S. Bureau of Reclamation,
Denver Federal Center,
Denver, Colorado

E. W. Lane and W. M. Borland

MEASUREMENT OF BED-LOAD SEDIMENT

The large-scale development of streams is currently accompanied by a growing awareness among engineers that most streams cannot be considered simply as flows of water, but must be considered as flows of water transporting solids in solution, in suspension, and by hydraulic shear on the stream bed. This flow of solids is as important in the geomorphic cycle as the stream flow is in the hydrologic cycle. The chemical and physical quality of a stream, determined by the solids in transport, must necessarily affect the design and development of related water control structures and projects. The chemical quality of the water of any stream can be obtained with a high degree of precision if sufficient samples are obtained. Likewise, if a sufficient number of suspended sediment samples can be obtained, the suspended sediment load can be determined for any stream. However, the sediment transported by hydraulic shear on the stream bed, or bed load, cannot be measured directly by practical methods except on small streams.

Most investigators of fluvial sediments are confident that equations will be developed which will permit practical determination of that part of the total sediment load of a stream which is coarser than the finest particle found in the stream bed. A great deal of field data on bed loads of various streams with various types of sediment will be needed in the development and refinement of the theory. Regardless of the degree of refinement possible in bed-load equations and analytical solutions in general, fluvial sediment investigations can never be an exact science. The multitude of variables, and particularly their variation with time, defies exact analysis, so that major dependence should be placed on field measurements.

Methods of measurement--Two general methods that may be used for measuring the discharge of bed load are (1) to trap the bed load over a given period of time and measure it by weighing, and (2) to measure the total load with standard suspended sediment samplers at a turbulent section where the sediment is momentarily all in suspension. The first and more direct method has been investigated a number of times by engineers since about 1898. Development of a convenient bed-load sampler that is reliable under general field conditions has never been successful. Use of the US-series suspended-sediment samplers (Interdepartmental Committee, Progress Report, Comparative field tests on suspended sediment samplers, Washington, D. C., December 1944) for measurement of bed load has been considered for several years. In this approach bed load is defined as the difference between the total sediment load and the measured suspended load. The method consists of measuring the suspended load both at a normal stream cross section at a cross section

Fig. 1--Normal section on the Niobrara River near Cody, Nebraska, looking upstream; the natural flume of Figure 2 is about a quarter mile downstream from the gaging station

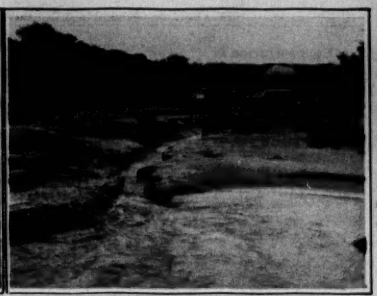


Fig. 2--Natural flume on the Niobrara River near Cody, Nebraska; the shelter housing the US D-43 sediment sampler is visible on the county bridge

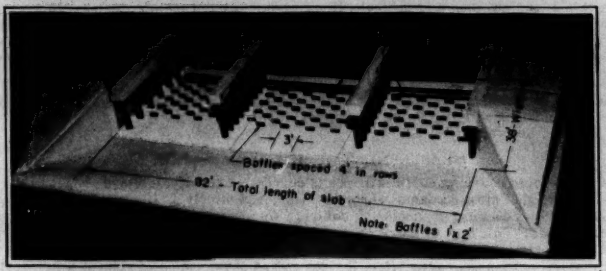


Fig. 3--Table model of the turbulence flume on the Middle Loup River at Dunning, Nebraska, showing dimensions and essential elements; the highway bridge above the flume has been removed from the model

where increased turbulence forces the bed load into suspension. If the turbulence is sufficient to suspend the total load at the sampling section momentarily, the difference between the loads measured at the cross section will represent the bed load.

A third method, which now appears promising, consists of a combination of suspended-load measurements and particle size analyses at both a normal cross section and a cross section where increased turbulence results in a measurable increase in the suspended portion of the total sediment load. Assuming (1) that samples of the material from the surface of the stream bed will give the particle size distribution of the bed load, and (2) that increased turbulence will suspend additional bed load up to some limiting particle size, then the particle size distribution of the suspended-load increment at the turbulent section should indicate the percentage of bed load that has gone into suspension. Thus it may be possible to utilize any reach of increased turbulence on a stream to obtain a practical measurement of the bed load.

Investigational program--Investigations of sediment transported as bed load are currently conducted on the Niobrara River near Cody, Nebraska (see Fig. 1 and 2), and the Middle Loup River at Dunning, Nebraska. At the former station, periodic measurements of bed load have been made at a natural flume for about two years. Figure 2 shows the contraction of the channel where the river is cutting through a siltstone bed. Measurements of the water discharge and normal suspended sediment load are made by wading about 30 ft downstream from the gage house shown at the right in Figure 1. The cableway is used during high flows. A study of suspended-load measurements and particle size analyses of the suspended load at this section and at a normal section

Fig. 4--Removable baffles of corrugated iron, one foot high and two feet wide, cause the energy of the stream to create the turbulence necessary to force the bed load into suspension; this picture was taken during construction, and shows a portion of the upstream cofferdam

Fig. 5--Sediment discharge measurement from downstream walkway of the turbulence flume includes depth-integration with the US DH-48 hand sampler; the sampler nozzle touches the six-inch measuring sill at the bottom of the sampling vertical

upstream, together with analyses of the bed material at the normal section, indicates that essentially the total sediment load is measured in suspension at the contacted section. Over 30 determinations indicate that the bed load at the normal section, by the difference between total and suspended load averages about 50 per cent of the total load, ranging from 24 to 68 per cent without apparent correlation with water or sediment discharge.

The turbulent section must be introduced artificially when none occurs naturally in the channel. When bed-load measurements were desired on the Middle Loup River in Nebraska, the most promising solution was to undertake the design and construction of a structure for inducing turbulence to suspend total sediment load. A site at Dunning, Nebraska, was chosen because of the straight and uniform channel available, and because of its key location with respect to proposed diversion projects for irrigation. The contract for the laboratory investigation and design of the

structure, to be known as a turbulence flume, was awarded to the Civil Engineering Section of the Colorado Agricultural Experiment Station, Fort Collins, Colorado.

Essential features of the turbulence flume are shown in Figure 3. Figure 4 shows the construction work, and Figure 5, the flume in use. The baffles and sills are fastened to a level floor of reinforced concrete. An important feature of the turbulence flume is that the baffles are easily rearranged, replaced with higher elements, or removed. As clearly anticipated from the laboratory study, no arrangement can eliminate considerable deposit around the first few rows of baffles. The criterion for success of the structure, that no appreciable quantity of material move as bed load over the measuring sill, has been satisfied.

The turbulence flume has been in operation only since June, 1949, and the bed-load data available are as yet too meager for generalization. However, the bed-load percentage appears similar in general magnitude to that of the Niobrara River near Cody. Both streams are characterized by a uniform base flow from the groundwater reservoir of the sandhill region. The sediment load of both streams originates largely from bank erosion and is essentially bed material in its particle size distribution. The mean size of the bed material at the Dunning flume location was determined to be 0.35 mm.

In order that the data of these investigations be of value in analytical study of bed-load movement, measurements of water surface slopes, water temperatures, and particle size analyses of bed material and suspended loads are made in conjunction with the water and sediment discharge measurements. A water-stage recorder was installed immediately upstream from the turbulence flume at Dunning. With the original stage recorder remaining in operation a quarter of a mile upstream since 1945, a continuous slope record is available. A water and air temperature recorder is also in operation at the site.

In addition to the measurements discussed, thorough investigation requires data on concurrent velocity and concentration profiles at the two or more sections to be studied at Dunning and near Cody. The cableway over the Niobrara River as shown in Figure 1 enables use of the 100-lb US P-46 point-integrating sampler at a normal measuring section. It also permits necessary sediment discharge measurements at high stages.

Since field data on sediment transportation as bed load are scarce, and generally difficult to obtain, effort is being made in these investigations to obtain all the information of value in defining the validity of the various bed-load equations developed in the laboratory. Analysis of a sufficient quantity of this type of data will eventually produce the analytical tools needed by engineers in approaching a solution to many sedimentation problems.

Eugene F. Serr III

U. S. Geological Survey,
Lincoln, Nebraska

REVIEWS, ABSTRACTS, AND BIBLIOGRAPHY

REVIEWS AND ABSTRACTS

BIRKHOFF, GARRETT, Hydrodynamics, published for Univ. of Cincinnati by Princeton Univ. Press, 186 pp., 1950.

This new work is not another technical presentation of the methods and results of the classical theory of fluid mechanics. Rather it is a critical reappraisal of some of the fundamental assumptions and paradoxical results, as well as a review of some of the recent developments of this theory. It is intended primarily for a reader already familiar with the usual details and arguments of the classical theory, although the mathematical analysis is not particularly formidable.

Particular attention is paid to a careful examination of the usual reference to "viscous effects" to explain away gross discrepancies between theory and experiment. There is an extensive discussion of the free boundary theories of jets, wakes, and cavity flows. A re-examination of "modeling" theory and its origin in symmetry concepts leads to the application of group theoretic ideas and the mathematical theory of homogeneous spaces.

The reviewer found it a pleasure to read this stimulating new book, which he recommends to workers in this field.

S. A. SCHAAF

BIBLIOGRAPHY

BIBLIOGRAPHY: GEODESY

BAGLIETTO, E. E., Trabajos de la cátedra de geodesía, físicas y naturales, Univ. Buenos Aires, 40 pp., 1950.

BAKULIN, P. I., Fundamental catalogue of stars, Gos. izd-vo tekhniko-teoret. lit-ry, Moscow, 236 pp., 1949 (in Russian).

BROCKS, KARL, Meteorologische Hilfsmittel der geodätischen Höhenmessung, Zs. Vermessungswesen, pp. 71-76, 110-116, 145-152, March, April, May 1950.

BULANZHE, I. D., Formulas and tables for use in gravimetric observations, Izd-vo geodezicheskei i Kartograficheskei lit-ry, Moscow, 227 pp., 1949 (in Russian).

CECCHINI, GINO, Le variazone di latitude e il movimento del polo di rotazione terrestre, Bull. Geod., no. 17, pp. 325-361, Sept. 1950.

CHEN, C. C., Notes on the H-variometer, J. Chinese Geophys. Soc., v. 2, no. 1, pp. 83-86, 1950.

CORPACIU, ALEXANDRE, La compensation conditionnelle et la fermeture d'un grand système annulaire, Bull. Géod., no. 17, pp. 278-293, Sept. 1950.

DURNEV, A. I., Professor F. N. Krassovski and his role in the development of Soviet geodetic science, Vsesoiuznoe Astronomo Geodezicheskoe Obshchestvo, Bull. no. 8 (15), pp. 3-7, 1950 (in Russian).

FERNANDEZ DE LA PUENTE, F., El astrolabio de prisma como instrumento de posición, Urania, v. 34, no. 220, pp. 11-23, 1949.

GOUGENHEIM, ANDRE, Sur une nouvelle méthode d'astronomie géodésique, C.-R. Acad. Sci., Paris, no. 15, pp. 684-688, 9 Oct. 1950.

HAALCK, HANS, Die vollständige Bestimmung örtlicher gravimetrischer Störungsfelder aus Drehwaagemessungen mit Berechnungsbeispiel, Deutsche Acad. Wiss. Berlin, Veröff. Geod. Inst., Potsdam, no. 4, pp. 1-41, 1950.

HAALCK, HANS, Das physikalische Bildungsgesetz der Figur der Erde, Deutsche Acad. Wiss. Berlin, Veröff. Geod. Inst., Potsdam, no. 4, pp. 43-53, 1950.

HAGIWARA, T., T. RIKITAKE, and J. YAMADA, Observations of the deformation of the Earth's surface at Aburatsubo, Miura Peninsula, pt. I, Bull. Earthquake Res. Inst., Tokyo Univ., v. 26, pp. 23-26 + 1 pl., 1948.

HARKINK, F., Les conditions du canevas (Essai d'un exposé rigoureux), Bull. Géod., no. 17, pp. 245-266, Sept. 1950.

HEISKANEN, W., Isostatic studies in various countries, Bull. Géod., no. 17, pp. 235-244, Sept. 1950.

HEISKANEN, W., The Finnish 864 m long Nummela standard base line measured with Väisälä light interference comparator, Bull. Géod., no. 17, pp. 294-298, Sept. 1950.

HONKASALO, TAUNO, Measuring of the 864 m long Nummela standard base line with the Väisälä light interference comparator and some investigations into invar wires, Suomen Geod. Laitoksen Julkaisuja, Helsinki, no. 37, 88 pp., 1950.

IVANOV, V. K., On the determination of harmonic moments of the disturbing mass for obtaining the gravitational potential, carried out in the plane, Izvestia Seriia geograficheskaia i geofizicheskaia Akademia Nauk, v. 14, no. 5, pp. 403-414, 1950 (in Russian).

JENSEN, H., Formulas for the astronomical correction to precise levelling, Bull. Géod., no. 17, pp. 267-277, Sept. 1950.

KILCHLING, K., Zur Eötvösschen Drehwaage, Ber. Naturf. Gesellschaft, Freiburg, pp. 225-234, 1943-1949.

KU, K. G., and YOUNGTSEN CENG, Isostatic anomalies of 208 Chinese gravity stations (second paper), J. Chinese Geophys. Soc., v. 2, no. 1, pp. 14-26, 1950.

LAMBERT, W. D., The International Geodetic Association (Die Internationale Erdmessung) and its predecessors, Bull. Géod., no. 17, pp. 299-324, Sept. 1950.

MUKHERJEE, S. M., and C. S. KARVE, Visibility at the Colaba Observatory, Bombay, Indian J. Met. and Geophys., v. 1, no. 3, pp. 220-228, 1950.

NEKLIUDOVA, N. F., On a method of the determination of the figure of the Earth, Bull. Instituta teoreticheckon Astronomii, v. 4, no. 8 (61), pp. 408-413, 1950 (in Russian).

OLANDER, V. R., On the geoid in the Baltic area and the orientation of the Baltic ring, Geod. Inst., Finland, Veröff. No. 38, 25 pp., 1950.

PUTILIN, I. I., Observations of the total solar eclipse of July 9, 1945, Vsesoiuznoe Astronomo Geodezicheskoe Obshchestvo, Bull. no. 4 (11), pp. 3-9, 1948 (in Russian).

RICHTER, HANS, Photogrammeter in Arktis und Antarktis, Polar Forschung, v. 15, no. 1/2, pp. 1-4, 1945.

SCHLEUSENER, H., Grundlagen der grossregionalen Gravimetermessungen für das Amt für Bodenforschung, Geol. Jb., 1943-1948, Geol. Landesanstalten, Deutschland, v. 64, pp. 187-199, 1950.

WERKE, ASKANIA, Théodolite de précision Askania d'après Gigas avec enregistrement photographique, Bull. Géod., no. 17, pp. 362-370, Sept. 1950.

WOLF, HELMUT, Numerische Untersuchungen zur astronomisch-geodätischen Netzausgleichung, Astronomische Nachrichten, Berlin, v. 278, no. 3, pp. 133-136, Feb. 1950.

WOLF, H., Beiträge zum Zusammenschluss von Dreiecksnetzen, Inst. Erdmessung, Bamberg, Veröff. 10, 142 pp., 1950.

ZAGREBIN, D. V., The different principal moments of inertia of the triaxial ellipsoid, Bull. Inst. teoreticheckon Astronomii, v. 4, no. 8 (61), pp. 390-401, 1950 (in Russian).

ZAGREBIN, D. V., The determination of the undulated geoid with calculations of correction terms for a condensed Earth's ellipsoid, Bull. Inst. teoreticheckon Astronomii, v. 4, no. 8 (61), pp. 402-407, 1950 (in Russian).

ZHONGOLOVICH, I. D., Conventional applications of the classical Stokes formula, Bull. Inst. teoreticheckon Astronomii, v. 4, no. 6 (59), pp. 270-282, 1950 (in Russian).

ZHONGOLOVICH, I. D., Several Stokes constants for the standard triaxial ellipsoid, Bull. Inst. teoreticheckon Astronomii, v. 4, no. 8 (61), pp. 375-389, 1950 (in Russian).

BIBLIOGRAPHY: SEISMOLOGY

AKIMA, T., A torsional pendulum low-pass filter applied to the study of earthquake waves, pt. 2, Bull. Earthquake Res. Inst., Tokyo Univ., v. 27, pp. 69-74, 1949.

DARBYSHIRE, J., Identification of microseismic activity with sea waves, Proc. R. Soc., ser. A, v. 202, pp. 439-448, 1950 [abst. in Physics Abstracts, v. 53, no. 634, p. 872, 1950].

HAARSTICK, F., Die Weg-Zeitkurve in der Reflexionsseismik, Geol. Jb., 1943-1948, Geol. Landesanstalten, Deutschland, v. 64, pp. 173-185, 1950.

IKEGAMI, R., On the vibrations of a building caused by microseisms, Bull. Earthquake Res. Inst., Tokyo Univ., v. 27, pp. 81-84, 1949.

IKEGAMI, R., and F. KISHINOUYE, A study on the propagation of microseismic waves, Bull. Earthquake Res. Inst., Tokyo Univ., v. 27, pp. 75-80, 1949.

INGLADA, VICENTE, Métodos macrosísmicos de determinación de la profundidad focal, Rev. Geofís., Madrid, v. 9, no. 34, pp. 123-146, 1950 (summary in English).

KANAI, K., On the existence of the M_2 waves in actual seismic disturbance, Bull. Earthquake Res. Inst., Tokyo Univ., v. 26, pp. 57-60, 1948.

KANAI, K., Relation between the earthquake damage of non-wooden buildings and the nature of the ground, Bull. Earthquake Res. Inst., Tokyo Univ., v. 27, pp. 97-100, 1949.

KANAI, K., T. TANAKA, and T. SUZUKI, Vibration experiments with the actual buildings, Bull. Earthquake Res. Inst., Tokyo Univ., v. 27, pp. 91-95, 1949.

MACELWANE, JAMES B. (editor), Twenty-fifth anniversary commemorative volume, Jesuit Seismological Association, 1925-1950, 347 pp., 1950. (Twenty-three chapters arranged in two parts describing the origin of the Association and its work, by 11 authors. An extensive bibliography is also included.)

MENIS, S., and C. MORELLI, Contribution to the study of the so-called "principal phase" of a seismogram, Ann. Geofis., v. 2, pp. 545-575, 1949 (in Italian) [abstr. in Physics Abstracts, v. 53, no. 633, p. 781, 1950].

MILNE, W. G., Bibliography of seismology, items 7222-7417, January to June, 1950, Pub. Dominion Obs., Ottawa, v. 14, pp. 147-164, 1950.

MINAKAMI, T., Recent activities of Volcano Usu, pt. 3; Earthquakes at the stage of paroxysmal eruption, Bull. Earthquake Res. Inst., Tokyo Univ., v. 27, pp. 123-128 + 3 pl., 1950.

MINAKAMI, T., Recent activities of Volcano Usu, pt. 4; Earthquakes followed by the birth and development of the lava dome, Bull. Earthquake Res. Inst., Tokyo Univ., v. 27, pp. 129-134, 1950.

MIYAMURA, S., Tertrema movado kaj kvalito de grundo ĉirkaŭ la urbeto de Gobo, Wakayama prefekto, Bull. Earthquake Res. Inst., Tokyo Univ., v. 26, pp. 101-104, 1948 (in Esperanto).

MUKHERJEE, S. M., Remarks on two Hindukush earthquake shocks, Indian J. Met. Geophys., v. 1, no. 4, pp. 297-302, 1950.

NASU, N., Field determination of the elastic property of soil layers, pt. 1, Bull. Earthquake Res. Inst., Tokyo Univ., v. 27, pp. 101-106, 1949.

NASU, N., Block movement along the seismic fault, pt. 1 (Fukui fault and others), Bull. Earthquake Res. Inst., Tokyo Univ., v. 27, pp. 27-33, 1949.

OMOTE, S., Earthquake damages in Yokohama City due to the Great Kwanto Earthquake of September 1, 1923, Bull. Earthquake Res. Inst., Tokyo Univ., v. 27, pp. 57-62, 1949.

OMOTE, S., On the coda waves of earthquake motions, pt. 4, Bull. Earthquake Res. Inst., Tokyo Univ., v. 27, pp. 49-55, 1949.

OMOTE, S., The relation between the earthquake damages and the structure of the ground in Yokohama, Bull. Earthquake Res. Inst., Tokyo Univ., v. 27, pp. 63-68, 1949.

OMOTE, SYUN'ITIRO, On the coda waves of earthquake motions, pt. 4, Spec. Bull. no. 7, Earthquake Res. Inst., Tokyo Univ., 97 pp., 1949 (in Japanese with summary in English).

PRESS, F., M. EWING, and I. TOLSTOY, The Airy phase of shallow-focus submarine earthquakes, Bull. Seis. Soc. Amer., v. 40, pp. 111-148, 1950 [abstr. in Physics Abstracts, v. 53, no. 634, p. 872, 1950].

SATÔ, Y., Relation between seismic intensity and epicentral distance, Bull. Earthquake Res. Inst., Tokyo Univ., v. 26, pp. 91-93, 1948.

SATÔ, Y., Boundary conditions in the problem of generation of elastic waves, Bull. Earthquake Res. Inst., Tokyo Univ., v. 27, pp. 1-9, 1949.

SCHULZE, G. A., and O. FÖRTSCH, Die seismischen Beobachtungen bei der Sprengung auf Helgoland am 18. April 1947 zur Erforschung des tieferen Untergrundes, Geol. Jb., 1943-1948, Geol. Landesanstalten, Deutschland, v. 64, pp. 205-242, 1950.

SHIMOZURU, D., Study on the coefficient of internal friction of materials used in civil engineering and architectural structures (1st rep.), Bull. Earthquake Res. Inst., Tokyo Univ., v. 27, pp. 85-89 + 2 pl., 1949.

TAKAHASHI, T., and Y. SATÔ, On the theory of elastic waves in granular substance, pt. 1, Bull. Earthquake Res. Inst., Tokyo Univ., v. 27, pp. 11-16, 1949.

TANDON, A. N., Microseisms, Indian J. Phys., v. 24, pp. 80-90, 1950 [abstr. in Physics Abstracts, v. 53, no. 634, p. 872, 1950].

VOLK, J. A., and F. ROBERTSON, The electronic seismograph, Bull. Seis. Soc. Amer., v. 40, pp. 81-93, 1950 [abstr. in Physics Abstracts, v. 53, no. 635, p. 959, 1950].

BIBLIOGRAPHY: METEOROLOGY

ALBRECHT, F., Untersuchungen über den Wärmehaushalt der Erdatmosphäre und seine thermodynamische Bedeutung, Berichte, Deutsch. Wetterdienstes, US-Zone, no. 17, 70 pp., 1950.

ARAKAWA, H., On the visibility in the NW-Pacific, Papers in Met. Geophys., Met. Res. Inst., Tokyo, v. 1, no. 1, pp. 58-66, 1950.

AZPIROZ YOLDI, M., The affinity in thermodynamic processes of meteorological interest, Rev. Geofis., v. 9, pp. 42-72, 1950 (in Spanish) [abstr. in Physics Abstracts, v. 53, no. 635, p. 960, 1950].

BERKES, Z., Synoptische Untersuchungen einiger Singularitäten, Idöjárás, v. 54, no. 7-8, pp. 199-203, 1950 (in Hungarian with summary in German, p. 255).

BINTIG, PAUL, Der Einfluss des Windes auf die Wassertemperaturen des Ozeans und ihr Zusammenwirken mit der Lufttemperatur, Ann. Met., Hamburg, v. 3, pp. 193-201, 1950 (summary in English).

BOWER, S. MORRIS, Recent work of the Thunderstorm Census Organization, Q. J. R. Met. Soc., v. 76, no. 330, pp. 455-465, 1950.

BROOKS, C. E. P., C. S. DURST, N. CARRUTHERS, D. DEWAR, and J. S. SAWYER, Upper winds over the world, Geophys. Mem. No. 85, London, v. 10, 150 pp., 1950.

DAS, P. K., The growth of cloud droplets by coalescence, Indian J. Met. Geophys., v. 1, pp. 137-144, 1950 [abstr. in Physics Abstracts, v. 53, no. 634, p. 874, 1950].

DAVIES, D. R., Three-dimensional turbulence and evaporation in the lower atmosphere, Q. J. Mech. Appl. Math., v. 3, pp. 51-73, 1950 [abstr. in Physics Abstracts, v. 53, no. 634, p. 874, 1950].

DUE ROJO, A., Microturbonadas, Urania, v. 34, no. 220, pp. 130-135, 1949.

EUWE, W., Forecasting rainfall in the periods December-January-February and April-May-June for parts of Celebes and South Borneo, Met. Geophs. Dienst, Kon. Mag. Met. Obs., Batavia, Verhandelingen no. 38, 24 pp., 1950.

FRANKENBERGER, ERNST, Konvektion durch Ausstrahlung, Ann. Met., Hamburg, v. 3, no. 7-8, pp. 244-248, 1950 (summary in English).

FRITZ, SIGMUND, and GENE C. STEVENS, Atmospheric ozone at Washington, D. C., Mon. Wea. Rev., v. 78, no. 8, pp. 135-147, 1950.

GERMANY, METEOROLOGISCHES AMT FÜR NORDWESTDEUTSCHLAND, Bericht über die Tätigkeit in dem Jahrfünft 1945 bis 1949, 75 pp. + 5 charts, 1950.

GODSKE, C. L., and H. SCHIELDRUP PAULSEN, The forest precipitation, University of Bergen, 1949 yearbook, Nat. Rek. 8, 38 pp., 1950.

HAUER, H., and Others, Klima und Wetter der Zugspitze, 50 Jahre meteorologische Beobacttung des Observatorium Zugspitze, Berichte, Deutsch. Wetterdienstes, US-Zone, no. 16, 200 pp. + 5 pl., 1950.

HENNEBERGER, CHARLOTTE, Tagesgang und Komponenten der Abkühlungsgrösse, Archiv für Met., Geophys. und Bioklim., Ser. B, v. 2, pp. 86-119, 1950 (summary in English).

HOOPER, J. E. N., and A. A. KIPPAX, Radar echoes from meteorological precipitation, Proc. Inst. Elect. Engrs., pt. 1, v. 97, pp. 89-97, 1950 [abstr. in Physics Abstracts, v. 53, no. 634, p. 874, 1950].

HOOPER, J. E. N., and A. A. KIPPAX, The bright band--a phenomenon associated with radar echoes from falling rain, Q. J. R. Met. Soc., v. 76, pp. 125-132, April, 1950 [abstr. in Physics Abstracts, v. 53, no. 634, p. 874, 1950].

JAMES, R. W., On the theory of large-scale vortex motion in the atmosphere, Q. J. R. Met. Soc., v. 76, pp. 255-276, 1950 [abstr. in Physics Abstracts, v. 53, no. 635, p. 959, 1950].

JOHNSON, MAXWELL O., Cycles in weather and solar activity, Paradise of the Pacific Press, Honolulu, 224 pp., 1950.

JONES, H. SPENCER, The evolution of the Earth's atmosphere, Sci. Progr., v. 38, pp. 417-429, 1950 [abstr. in Phys. Abstr., v. 53, no. 633, p. 783, 1950].

JONES, R. F., The temperatures at the tops of radar echoes associated with various cloud systems, Q. J. R. Met. Soc., v. 76, pp. 312-330, 1950 [abstr. in Physics Abstracts, v. 53, no. 635, p. 960, 1950].

JORDAN, K., Remarques sur la définition plus complète du climat, Idöjárás, v. 54, no. 7-8, pp. 197-198, 1950 (in Hungarian with summary in French, p. 255).

KIVELIOVITCH, M., A note on Kibel's method of weather prediction, J. Sci. Met., v. 1, pp. 72-74, 1949 (in French with summary in English) [abstr. in Applied Mechanics Reviews, v. 3, no. 10, p. 327, 1950].

KÖHLER, HILDING, On evaporation from snow surfaces, Arkiv für Geofysik, Kungl. Svenska Vetenskap., v. 1, pp. 159-185, 1950.

KÖHLER, H., On the problem of condensation in the atmosphere, Nova Acta Reg. Soc. Sci. Upsaliensis, v. 14, no. 9, 75 pp., 1950 [abstr. in Physics Abstracts, v. 53, no. 635, p. 961, 1950].

KOO, CHEN-CHAO, Some aspects of the cutoff cyclonic vortices, J. Chinese Geophys. Soc., v. 2, no. 1, pp. 104-120, 1950.

LAMB, H. H., Types and spells of weather around the year in the British Isles: Annual trends, seasonal structure of the year, singularities, Q. J. R. Met. Soc., v. 76, no. 330, pp. 393-438, 1950.

MASUDA, Y., On the method of computing vertical motion in the atmosphere, Papers in Met. Geophys., Met. Res. Inst., Tokyo, v. 1, no. 1, pp. 1-28, 1950.

MILLER, SANFORD R., and WOODROW W. DICKEY, An objective method of forecasting winter-time precipitation, Mon. Wea. Rev., v. 78, pp. 161-169, 1950.

MÖRIKOFER, W., Die Klimaverhältnisse von Wiesen, Jahresber. Naturf. Gesellschaft, Graubündens, v. 82, pp. 53-88, 1950.

MULL, S., and Y. P. RAO, Dynamics of thunderstorms; pt. II: Origin of downdrafts in a thunderstorm and the circulation in a full-fledged thunderstorm cell, Indian J. Met. Geophys., v. 1, no. 4, pp. 291-297, 1950.

ORR, J. L., D. FRASER, and K. G. PETTIT, Analysis of experiments on inducing precipitation, Nat. Res. Counc. Canada Mech. Eng. Rep. no. MD-32, 10 pp., 1949 [abstr. in Applied Mechanics Reviews, v. 3, no. 11, p. 391, 1950].
PENMAN, H. L., Evaporation over the British Isles, Q. J. R. Met. Soc., v. 76, no. 330, pp. 372-383, 1950.
PERSON, HERMANN, Entwicklung und Einsatz von unbemannten automatischen Wetterfunkstationen im Polargebiet, Polar Forschung, v. 18, no. 1/2, pp. 6-9, 1948.
RAMASWAMY, C., and K. C. MAJUMDAR, The general characteristics of squalls at Peshawar, Mem. India Met. Dept., v. 28, pt. 1, 18 pp. + 14 tables + 8 pl., 1950.
RAMDAS, L. A., Rainfall and agriculture: Use of routine rainfall reports for crop outlooks, Indian J. Met. Geophys., v. 1, pp. 262-274, 1950.
RODEWALD, MARTIN, Wolkenstrassen über Holstein, Ann. Met., Hamburg, v. 3, pp. 202-213, 1950 (summary in English).
RODEWALD, MARTIN, Zur Frage der Winter-Vorbereitung durch die Zirkulationsentwicklung vom Oktober bis Dezember, Ann. Met., Hamburg, v. 3, no. 7-8, pp. 225-240, 1950 (summary in English).
SANDERSON, MARIE, Measuring potential evapotranspiration at Norman Wells, 1949, Geogr. Rev., Amer. Geogr. Soc. N. Y., pp. 636-645, October, 1950.
SELLICK, N. P., Equatorial circulations, Q. J. R. Met. Soc., v. 76, pp. 89-94, 1950 [abstr. in Applied Mechanics Reviews, v. 3, no. 10, p. 327, 1950].
SIESLACK, GÜNTER, Bemerkungen zur Trägheitskorrektion bei Höhentemperaturmessungen, Ann. Met., v. 3, pp. 160-162, 1950.
SUMNER, E. J., The significance of vertical stability in synoptic development, Q. J. R. Met. Soc., v. 76, no. 330, pp. 384-392, 1950.
TAO, SHIH-YEN, The moist and dry climate of China, J. Chinese Geophys. Soc., v. 2, no. 1, pp. 121-130, 1950.
TEPPER, MORRIS, Radar and synoptic analysis of a tornado situation, Mon. Wea. Rev., v. 78, pp. 170-176, 1950.
TROJER, H., Ein Beitrag zu einer dynamischen Klimatologie, Urania, v. 34, no. 220, pp. 112-129 + 1 pl., 1949.
WIERZEJEWSKI, H., Theoretisches und Konstruktives zur Messung der Abkühlungsgrösse, Archiv für Meteorologie, Geophysik und Bioklimatologie, v. 2, pp. 65-85, 1950 (summary in English).
WILKES, M. V., Oscillations of the Earth's atmosphere, Cambridge University Press, 74 pp., 1949 [abstr. in Physics Abstracts, v. 53, no. 634, p. 873, 1950].

BIBLIOGRAPHY: TERRESTRIAL MAGNETISM AND ELECTRICITY

ÁCS, ERNŐ, Eszköz a Földi mágneses tér gradiensének meghatarozasára (Instrument pour la détermination des gradients du champ magnétique terrestre), Földméréstani Közlemények, Budapest, v. 2, p. 24, 1950 (summary in French).
BULLARD, E. C., The origin of the Earth's magnetic field, Observatory, v. 70, pp. 139-143, 1950.
BURKHART, K., The general theory of the earth inductor, Geofis. Pura Appl., v. 15, pp. 69-89, 1949 (in German).
GRENET, G., Variomètre électromagnétique pour l'enregistrement des variations rapides du champ magnétique terrestre, Ann. Geophys., v. 5, p. 188, 1949.
HARNISCHMACHER, E., Solar influence on the normal E-layer of the ionosphere, C.-R. Acad. Sci., Paris, v. 230, pp. 1301-1302, 1950 (in French) [abstr. in Physics Abstracts, v. 53, no. 633, p. 783, 1950].
HARVEY, G. N., Magnetic compass problems--a fresh approach, Inst. of Navigation J., v. 2, p. 230, 1949.
HELWIG, W. F., Atmospheric electricity, Texas J. Sci., v. 1, pp. 19-22, 1949 [abstr. in Physics Abstracts, v. 53, no. 633, p. 786, 1950].
KATO, Y., and R. Shoji, New type of the earth inductor and its use for the prospecting of the underground structure, Tohoku Univ. Sci. Rep., Geophys., v. 1, p. 50, 1949.
KOSHIKAWA, YOSHIAKI, Magnetic survey in the area of topographical deformation of Volcano Usu, Bull. Earthquake Res. Inst., v. 27, pp. 21-25, 1949.
MACHT, HANS G., Die Wanderung des magnetischen Nordpols und sein mehrfaches Auftreten, Polar Forschung, v. 17, no. 1/2, pp. 133-139, 1948.
MACHT, HANS G., Die Lage des magnetischen Nordpols, Polar Forschung, v. 18, pp. 4-6, 1948.
MARTYN, D. F., Daily magnetic variations near the equators, Nature, v. 163, p. 685, April 30, 1949.
MAY, W. E., Ring-shaped compass needles, Nautical Mag., v. 163, p. 78, 1950.
RIKITAKE, T., A method for studying the distribution of electric currents in a spherical shell having non-uniform conductivity, Bull. Earthquake Res. Inst., Tokyo Univ., v. 26, pp. 11-15 + 1 table, 1948.

RIKITAKE, T., A study on regional anomaly in the Earth's magnetic field, Bull. Earthquake Res. Inst., Tokyo Univ., v. 26, pp. 17-21, 1948.
ROBERTS, G. E., Aerial magnetic survey, J. Inst. Navig., London, v. 3, pp. 121-132, 1950.
ROMAÑA, ANTONIO, and J. O. CARDÚS, Contribución al estudio de la influencia de la luna en las corrientes telúricas, Pub. Obs. Ebro, Misc. no. 6, 14 pp., 1949 (summary in French).
RYDBECK, OLOF E. H., A theoretical survey of the possibilities of determining the distribution of the free electrons in the upper atmosphere, Trans. Chalmers Univ. Tech., Gothenburg, Sweden, no. 3, 75 pp., 1942.
RYDBECK, OLOF E. H., On the spherical and spheroidal wave functions, Trans. Chalmers Univ. Tech., Gothenburg, Sweden, no. 43, 34 pp., 1945.
SANDNER, WERNER, Nordlichtbeobachtungen in Grönland 1911/1931, Polar Forschung, v. 2, no. 1/2, pp. 287-292, 1949.
SIMAMURA, H., and I. ICHIMURA, On the intensities and altitudes of the night-sky light, Papers in Met. Geophys., Met. Res. Inst., Tokyo, v. 1, no. 1, pp. 153-160, 1950.
SIMPSON, G., Atmospheric electricity during disturbed weather, Geophys. Mem. Met. Off., no.. 84, 51 pp., 1949 [abstr. in Physics Abstracts, v. 53, no. 634, p. 876, 1950].
SIVARAMAKRISHNAN, M. V., Some geomagnetic disturbances at Alibag Observatory (India) and allied radio and solar effects (1937-1946), Indian J. Met. and Geophys., v. 1, no. 3, pp. 207-219, 1950.
TIKHONOV, A. N., On the uniqueness of the solution of the problem of electro-prospecting, Dokl. Akad. Nauk, SSSR, v. 69, no. 6, pp. 797-800, 1949 (in Russian) [abstr. in Physics Abstracts, v. 53, no. 633, p. 782, 1950].
UNSÖLD, A., and S. CHAPMAN, Optical and radiofrequency absorption by solar corpuscular bursts, Observatory, v. 69, p. 219, 1949.
WALDMEIER, MAX, Radioastronomie, Astron. Mitteilungen der Eidgenössischen Sternwarte, no. 166, Verhandlungen der Schweizer. Naturforschenden Gesellschaft, Lausanne, pp. 24-36, 1949.
WALDMEIER, MAX, Die Natur der M-Regionen, Astron. Mitteilunger der Eidgenössischen Sternwarte, No. 167, Zürich, Zs. für Astrophysik, v. 27, pp. 42-48, 1950.
WATSON, R. A., and D. H. McINTOSH, Sudden commencements in geomagnetism, letter in Nature, London, v. 165, p. 1018, 1950.
WULF, OLIVER R., and SETH B. NICHOLSON, The production of geomagnetic activity--the activity of the years 1941 and 1942, Astr. Soc. Pac. Pub., v. 61, p. 166, 1949.
WULF, OLIVER R., and SETH B. NICHOLSON, Solar flares and moderate geomagnetic activity, Astr. Soc. Pac. Pub., v. 62, pp. 202-210, 1950.

BIBLIOGRAPHY: OCEANOGRAPHY

In this issue the recent Russian works in the field are continued from pp. 310-312 of the Transactions for April 1949. Additional journals represented are: Nauchnyi Biulletin' (Science Bulletin), Zhurnal Tekhnicheskoi Fiziki (Journal of Technical Physics); Izvestiia, Akademiia Nauk SSSR, Seriia Geologicheskaia; Zhurnal Eksperimental'noy i Teoreticheskoy Fiziki; and Voprosy Geografii (Questions of Geography).

AGENEROV, V. K., O dinamike vod Barentsova moria (Dynamics of the Barents Sea), Moskva, Gidrometeoizdat, 130 pp., 1946.
ANASTASEVICH, V. S., The nature of the echo in the sea, Zhur. Tekh. Fiz., v. 16, pp. 371-373, 1946.
BARANOV, I. V., Hydrochemical characteristics of the northern part of the Onezhskaya Guba, Nauchnyi Biull., no. 13, pp. 19-20, 1946.
BEREZKIN, VSEVOLOD, Dinamika moria (Dynamics of the sea), 683 pp., Gidrometeorologicheskoe Izd-vo, Sverdlovsk, 1947.
BREKHOVSKIKH, L. M., The propagation of sound in an underwater channel, Dok. Akad. Nauk, v. 69, pp. 157-160, 1949.
BRUEVICH, S. V., Rate of formation of bottom deposits in the Caspian Sea, Izvest. Akad. Nauk, Ser. Geogr. Geofiz., v. 13, pp. 9-32, 1949.
DOBROLONSKY, S. V., On the diurnal variations of temperature in the surface layer of the sea and on heat currents at the sea-air interface, Dok. Akad. Nauk, v. 45, pp. 371-374, 1944.
ERMOLAEV, M. M., Lithogenesis of plastic clay marine sediments, Izvest. Akad. Nauk, Ser. Geol., no. 1, pp. 121-138, 1948.
FEDOROV, E. P., The influence of fluctuations in the ocean level, caused by the motion of the Earth's poles, on such motion, Dok. Akad. Nauk, v. 67, pp. 647-650, 1949.
GOLOLOBOV, I. K., The age of the present stage of the Black Sea, Dok. Akad. Nauk, v. 66, pp. 451-453, 1949 [abstr. in Chem. Abstr., 7387c, 1949].

GOLOLOBOV, I. K., and M. V. PIROGOVA, The upper boundary of the hydrogen sulfide region in the eastern portion of the Black Sea, Dok. Akad. Nauk, v. 63, pp. 179-182, 1948.

KAPITSA, P. I., The problem of the formation of sea waves by the wind, Dok. Akad. Nauk, v. 64, pp. 513-516, 1949.

KLENOVA, M. V., Geologiia moria (Marine geology), 495 pp. + 3 pl., Moskva, 1948.

KUDRITSKIY, D. M., New developments in stereophotographic surveying of wave roughness, Met. Gidrol., no. 4, pp. 66-74, 1948.

LEONT'EV, O. K., Rebuilding of the profile of an accumulative shore during the lowering of sea level, Dok. Akad. Nauk, v. 66, pp. 377-380, 1949.

MIRONOV, Electrodes for measurements in the sea, Dok. Akad. Nauk, v. 70, pp. 825-828, 1950.

MOROSHKIN, K. V., Energy dissipation in the Baltic Sea, Met. Gidrol., no. 3, pp. 41-51, 1948.

NAZAROV, V. S., Fluctuations of iciness in the North Atlantic regions, Met. Gidrol., no. 3, pp. 60-65, 1948.

PANOV, D. G., Results of charting the floors of Soviet seas, Izvest. Vses. Geogr. Obshch., v. 80, pp. 329-339, 1948.

ROZENBERG, L. D., A new phenomenon in hydroacoustics, Dok. Akad. Nauk, v. 69, pp. 175-176, 1949.

SAKS, V. N., The rate of accumulation of recent marine sediments, Priroda, v. 39, no. 6, pp. 24-33, June 1950.

SAKS, V. N., Problems of submarine valleys, Priroda, v. 37, no. 9, pp. 32-40, Sept. 1948.

SELIAKOV, H. I., Some observations on ice and the processes connected with its formation, Dok. Akad. Nauk, v. 70, pp. 821-824, 1950.

SHTOKMAN, W., The stationary distribution of tongue-shaped isotherms in the sea for changes in turbulent diffusion and speed of flow, Izvest. Akad. Nauk, Ser. Geogr. Geofiz., v. 8, pp. 176-187, 1944.

SHTOKMAN, V. B., Influence of the relief of the bottom on the direction of ocean currents, Priroda, v. 38, no. 11, pp. 10-23, 1949.

SHTOKMAN, V. B., Ekvatorial'nye protivotechniia v okeanakh, osnovy teorii [Bases of theory of the Equatorial Counter Current], Gidrometeorologicheskoe Izd-vo, Leningrad, 155 pp., 1948.

SHTOKMAN, V. B., Determination of the flow rate and density distribution in the cross-section of an infinite channel in relation to the effect of wind and lateral friction in the field of Coriolis force, Dok. Akad. Nauk, v. 71, pp. 41-44, 1950.

SHULEIKIN, V. V., Ocherki po fizike moria, (Outlines of the physics of the sea), Izd-vo, Akad. Nauk, 334 pp., Moskva, 1949.

SHULEIKIN, V. V., Physics of the sea as part of the science of Stalin's epoch, Izvest. Akad. Nauk, Ser. Geogr. Geofiz., v. 14, pp. 7-24, 1950.

SRETENSKII, L. N., Theory of waves (on the surface of the sea) caused by a source of oscillations of given frequency on the sea-bed, Izv. Akad. Nauk, Ser. Geogr. Geofiz., v. 13, pp. 473-496, 1949.

SRETENSKII, L. N., A planar problem on the propagation of waves generated in a tank by an underwater source, Izvest. Akad. Nauk, Odtel. Tekh. Nauk, no. 3, pp. 321-332, 1950.

STRAKHOV, N. M., Data on the regularity and mechanism of marine sedimentation, pt. 1, Black Sea, Izvest. Akad. Nauk, Ser. Geol., no. 2, pp. 49-90, 1947; pt. 2, Caspian Sea, ibid, no. 1, pp. 80-111, 1950.

STRAKHOV, N. M., Distribution of iron in the sediments of lake and sea systems and the factors controlling in, Izvest. Akad. Nauk, Ser. Geol., no. 4, pp. 30-50, 1948.

STRAKHOV, N. M., The true role of bacteria in the formation of carbonate rocks, Izvest. Akad. Nauk, Ser. Geol., no. 3, pp. 9-30, 1948.

TEODOROVICH, G. I., The meteoritic, geochemical phase of seas and salt water in general as a producer of petroleum, Dok. Akad. Nauk, v. 69, pp. 227-230, 1949.

TUGOLESOV, D. A., Causes of the transgressions and regressions of the Caspian Sea, Izvest. Akad. Nauk, no. 6, pp. 131-140, 1948.

TURBOVICH, L. T., Turbulent diffusion and its function in the evaporation of water from the ocean surface, Zh. Eks. Teor. Fiz, v. 17, no. 4, 6 pp., 1947.

ZENKOVICH, V. P., Erosion phenomena of the Caucasus shore of the Black Sea, Voprosy Geog., v. 4, pp. 155-158, 1947.

ZENKOVICH, V. P., Developing an abrasion design in the process of raising the sea level, Dok. Akad. Nauk, v. 63, pp. 183-186, 1948.

ZENKOVICH, V. P., Certain factors in the formation of sea benches, Dok. Akad. Nauk, v. 65, pp. 53-56, 1949.

ZENKOVICH, V. P., Preservation of low-relief forms on the bottom of a deep sea, Dok. Akad. Nauk, v. 73, pp. 67-69, 1950.

ZHIVAGO, A. V., and V. V. PETRIKEEV, Method of determining modifications of coastal relief of the sea bottom after storms, Izvest. Akad. Nauk, Ser. Geogr. Geofiz., v. 13, no. 2, pp. 151-153, 1949.

BIBLIOGRAPHY: VOLCANOLOGY

BAGCHI, T. C., On the petrology of the pillow lavas in the contact aureole of the Land's End granite, Q. J. Geol., Mining, Metal. Soc., India, v. 22, no. 1, pp. 1-5, 1950.

BRUET, EDMOND, and JEAN AUBRAT, Age probable de la grande éruption péléénne de la Soufrière de la Guadeloupe, C.-R. Acad. Sci., v. 231, no. 1, pp. 63-64, 1950.

BULLARD, E. C., The transfer of heat from the core of the Earth, Mon. Not. R. Astr. Soc., Geophys. Suppl., V. 6, pp. 36-41, 1950 [abstr. in Physics Abstracts, v. 53, no. 633, p. 782, 1950].

CHUDOBA, K. F., and J. FRECHEN, Über die plastische Verformung von Olivin, Neues Jb. Min. Abh., v. 81, no. 2, pp. 183-200, 1950.

COGNE, JEAN, Observations au sujet d'enclaves déplacées dans un granite près de St.-Nazaire (Loire-Inferieure), C.-R. Acad. Sci., v. 231, no. 20, pp. 1076-1078, 1950.

DEN TEX, E., Les roches basiques et ultrabasiques des lacs Robert et le Trias de Chamrousse (Massif de Belledonne), étude pétrologique et géologique, Leidse Geol. Med., Leiden, v. 15, pp. 1-204, 1950.

DE, S. KUMAR, and B. MUKHERJEE, The geology of the basic rocks around Jalwa (Jalve) Pahar, Santal Parganas, Q. J. Geol. Mining Metal. Soc., India, v. 21, no. 4, pp. 149-153, 1949.

EIGENFELD-MENDE, ILSE, Metamorphe Umwandlungserscheinungen an Metabasiten des Südschwarzwaldes, Mitt. Badischen Geol. Landesanstalt, N. F., v. 1, pp. 1-111, 1948.

ERDMANNSDÖRFFER, O. H., Die Entwickelung und jetzige Stellung des Granitproblems, Heidelberger Beitrage zur Min. Petrographie, v. 2, no. 4, pp. 334-377, 1950.

FAIRBRIDGE, R. W., Antarctica and geology, Scope, J. Sci. Union, Univ. Western Australia, v. 1, no. 4, pp. 25-30, 1949.

FIALA, FRANTISEK, and RUDOLF ROST, La Teschenite de Budňany et quelques autres roches diabasiques alcalines du silurien de la Bohême Centrale, Sbornik Národniho Musea v Praze (Acti Musei Nationalis Pragae) v. V. B. 1948, no. 8, Geol. Palent., no. 4, 43 pp., 1949.

GAME, P. M., Rocks collected by W. Thesiger in Oman, Arabia in 1946-7, Bull. British Museum, Mineralogy, v. 1, no. 1, pp. 15-24, 1950.

GHOSE, CHINMOY, A petro-chemical study of the lamprophyres and associated intrusive rocks of the Jharia Coalfield, Q. J. Geol., Mining, Metal. Soc. India, v. 21, no. 4, pp. 133-147, 1949.

GHOSH, P. K., The charnockite series of Bastar state and Western Jeypore, Records Geol. Sur. India, no. 75, Prof. Paper 15, pp. 1-55, 1941.

GROSEMANS, P., Note preliminaire concernant le metamorphisme des couches de Kikosa, Comité special du Katanga, v. 14, pp. 71-73, 1949.

GUILCHER, M. A., Définition d'un type de volcan "écossais," Bull. Assoc. Géogr. Français, no. 206-207, 10 pp., 1950.

HOENES, D., Magmatische Entwicklung und Tiefenstufen im Grundgebirge der Vogesen und des Schwarzwaldes, Ber. Naturf. Gesellschaft, Freiburg, pp. 197-224, 1943-1949.

HOLLAND, HEINRICH D., and J. LAURENCE KULP, Low level alpha counting of solids by the scintillation method, Tech. Rep. no. 1, Lamont Geol. Obs., Columbia University, New York, 30 pp. + 19 fig., 1950.

JÉRÉMINE, E., Contribution à l'étude pétrographique du Cameroun Occidental, Mém. Muséum National, Hist. Nat., Paris, N. S., v. 17, pp. 273-320 and atlas, 1943.

KAR, P., Pyroxenic gneisses and granulites from Angul, Orissa, Q. J. Geol., Mining, Metal. Soc. India, v. 21, no. 4, pp. 123-131, 1949.

KING, B. C., The Napak area of southern Karamoja, Uganda, Geol. Surv. of Uganda, Mem. 5, 1948, 57 pp., 1949.

KUNO, HISASHI, Geology of Hakone volcano and adjacent areas, pt. I, J. Fac. Sci., Univ. of Tokyo, v. 7, pp. 257-279, 1950.

LOKKA, L., Chemical analyses of Finnish rocks, Bull. Comm. Geol. Finlande, no. 151, 75 pp., 1950.

MILLMAN, A. P., Geochemical prospecting by the field analysis of surface waters, Mine and Quarry Engr., v. 16, pp. 145-148, 1950 [abstr. in Chem. Abstr., v. 44, no. 19, p. 8830, 1950].

NECHAEV, G. A., Volcanic tuffs and their decomposition on weathering, Dokl. Akad. Nauk SSSR, v. 75, no. 4, pp. 573-574, 1950 (in Russian).

NICKEL, ERWIN, Das Mischgestein vom Typus Eschenbach (Niederösterreich) und seine stellung im Rastenberger Tiefenkörper, Neues Jb. Min. Abh., v. 81, pp. 273-314, 1950.

PART, GERALD M., Volcanic rocks from the Cape Verde Islands, Bull. British Museum, Mineralogy, v. 1, pp. 25-72, 1950.

PULFREY, WILLIAM, Geological Survey of Maragoli Northern Kavirondo, Kenya Mining and Geological Dept., Rep. no. 9, pp. 1-54, 1946.

PULFREY, WILLIAM, Ijolitic rocks near Homa Bay, Western Kenya, Q. J. Geol. Soc., London, v. 105, pt. 4, no. 420, pp. 425-459, 1950.

ROY, C., Regional metamorphism in eastern Sikkim, Q. J. Geol. Mining, Metal. Soc. India, v. 21, pp. 155-170, 1949.

SANDREA, ANDRE, Sur la presence de högbomite dans une spilite du Cameroun, C.-R. Acad. Sci., v. 230, pp. 2306-2307, 1950.
SARMA, N. L., and Y. K. AGRAWAL, A note on the rapakivi structure in the epidiorite and injection gneiss of Dhanbad area, Q. J. Geol., Mining, Metal. Soc. India, v. 22, pp. 11-13, 1950.
SARMA, N. L., R. C. MISRA, and G. S. BHATNAGAR, A note on the cordierite-bearing vitrophyric and hornfelsic rocks of Ramnagar area, Raniganj coal field, Q. J. Geol. Mining, Metal. Soc. India, v. 22, pp. 7-9, 1950.
SAUER, K., Über vulkanische Bildungen in den Vorbergen von Ettenheim-Herbolzheim, Ber. Naturf. Gesellschaft, Freiburg, pp. 53-82, 1943-1949.
SCHÜRMAN, H. E. M. E., Massengesteine aus Ägypten, 14th pt., Neues Jb. Min. Abh., v. 81, pp. 200-272, 1950.
SIMONEN, AHTI, Three new boulders of orbicular rock in Finland, Bull. Comm. Geol., Finlande, no. 150, pp. 31-38, 1950.
SMITH, W. CAMPBELL, Note on the Kapiti phonolites and kenyites of Kenya Colony, Bull. British Museum, Mineralogy, v. 1, pp. 3-14, 1950.
SMYTHE, J. A., Metamorphism of rocks by the Whin sill, Proc. Univ. of Durham, Phil. Soc., v. 10, pt. 7, pp. 541-546, 1950.
TANEDA, S., Petrological discussion on magnetite, Geol. Soc., Japan, v. 55, no. 646, pp. 72-76, July 1949 (in Japanese with English summary).
TYNDALE-BISCOE, R., The geology of the country around Gwelo, Geol. Survey Bull. no. 39, Southern Rhodesia, 145 pp., 1949.
WADIA, D. N., On the occurrence of pumice on the East coast of Ceylon, Spolia Zeylanica, Geol., Zool., Anthropology, Ceylon, v. 24, pt. 1, pp. 1-2, 1944.
WEDEPOHL, K. H., Der Feldspatbasalt des "Hohen Hagen" bei Dransfeld, Heidelberger, Beitrage zur Min. Petrogr., v. 2, pp. 378-382, 1950.
ZIMENS, KARL-ERIK, Über die Messung radioaktiver Isotope, Trans. Chalmers Univ. Tech., Gothenburg, Sweden, no. 54, 58 pp., 1946.

BIBLIOGRAPHY: HYDROLOGY

ALEKIN, O. A., The problem of the channel classification of natural waters, Voprosy Gidrokhim, no. 32, pp. 25-39, 1946 (in Russian) [abstr. in Chem. Abstr., v. 44, no. 19, p. 9087, 1950.
ATWATER, M. M., Avalanche hazard forecasting and avalanche control, Western Snow Conf., Boulder City, Nevada, pp. 26-28, April 1950.
BADER, HENRI, The significance of air bubbles in glacier ice, J. Glaciology, v. 1, no. 8, pp. 443-451, 1950.
BAIRD, RALPH W., and WILLIAM D. POTTER, Rates and amounts of runoff for the Blacklands of Texas, U. S. Dept. Agri. Tech. Bull. 1022, 23 pp., July 1950.
BERTLE, F. A., and E. G. DUNFORD, A day's contribution to the snowmelt hydrograph, Western Snow Conf., Boulder City, Nevada, pp. 60-64, April 1950.
BLANEY, HARRY F., and WAYNE D. CRIDDLE, Determining water requirements in irrigated areas from climatological and irrigation data, U. S. Dept. Agr., SCS TP-96, 48 pp., Aug. 1950.
BROWN, RICHMOND F., Ground water in the vicinity of Brush, Colorado, Colo. Water Cons. Bd., Ground Water Series, Circular 2, 27 pp., 1950.
CARLÉ, WALTER, Geologie und Hydrologie der Heilwasser von Bad Mergentheim, Mitt. Geol. Abt. Württemberg Stat. Landesanst. no. 21, pp. 267-330, 1950.
CHILDS, E. C., The equilibrium of rain-fed ground water resting on deeper saline water, the Ghyben-Herzberg lens, J. Soil Sci., v. 1, no. 2, pp. 173-181, Jan. 1950.
CUNDIFF, STUART A., An industrial operation to produce precipitation, Western Snow Conference, Boulder City, Nevada, pp. 29-34, April 1950.
DAS, ISHAR, Theory of flow of water and universal hydraulics diagrams, J. Central Bd. Irrig., v. 7, pp. 151-162, March 1950.
DIAMOND, MARVIN, The use of double mass analysis in testing the consistency of climatological records, Western Snow Conf., Boulder City, Nevada, pp. 18-25, April 1950.
EAKIN, T. E., Preliminary report on ground water in Fish Lake Valley, Nevada and California, Nevada State Engineer, Water Res. Bull. 11, pp. 7-33, 1950.
FENT, O. S., Geology and ground-water resources of Rice County, Kansas, Univ. Kans. Pub., Bull. 85, 142 pp., 1950.
FERRIS, JOHN G., Memorandum concerning a pumping test at Gas City, Indiana, with a detailed discussion of the methods used in the quantitative analysis of water-well interference problems, Ind. Dept. Cons., Div. Water Res., Bull. 1, 23 pp., 1945.
GERDEL, R. W., and C. W. MANSFIELD, The use of radioisotopes in research on snow melt and runoff, Western Snow Conf., Boulder City, Nevada, pp. 5-17, April 1950.
GLOCK, WALDO S., Tree growth and rainfall, a study of correlation and methods, Smithsonian Misc. Coll. Pub. 4016, v. 3, no. 18, 47 pp., Oct. 25, 1950.

GOTTSCHALK, L. C., and GUNNAR M. BRUNE, Sediment design criteria for the Missouri Basin Loess Hills, Soil Cons. Serv., SCS-TP-97, 19 pp. + 12 tables, Milwaukee, Wisconsin, 1950 (processed).

HORBERG, LELAND, MAX SUTER, and T. E. LARSON, Ground water in the Peoria (Illinois) region, Ill. Geol. Surv., Bull. 75, 128 pp. + 4 pl., 1950.

HUBBELL, D. S., and J. L. GARDNER, Effects of diverting sediment-laden runoff from orroyos to range and crop lands, U. S. Dept. Agri. Tech. Bull. 1012, 53 pp., Aug. 1950.

JAKOBSEN, J. M., and K. HØJENDAHL, Investigation of methods and apparatus suitable for current control of the moisture in soil covered by crops, with C. P. LYSGAARD - Investigation with tensiometers holes for determining ground-water table and soil samples in the experimental field, R. Vet. and Agric. Col. Yearbook, Copenhagen, Denmark, 140 pp., 1950.

KLEIN, HOWARD, R. C. BAKER, and G. A. BILLINGSLEY, Ground-water resources of Jefferson County, Arkansas, Univ. Ark. Inst. Sci. Tech., Research Series 19, 44 pp., June 1950.

KNIGHT, A. G., The measurement of turbidity in water, J. Inst. Water Eng., v. 4, no. 6, pp. 449-458, Oct. 1950.

KOBAYASHI, JUN, Chemistry of irrigation water, Rep. Ohara Inst. Agr. Res., Nōgaku Kenkyū, v. 37, pp. 49-51, 1947 [abstr. in Chem. Abstr., v. 44, no. 17, p. 8025, 1950.

KOBAYASHI, JUN, Chemistry of irrigation water, pt. 2, Ohara Inst. Agr. Res., Kurashiki, v. 37, pp. 150-158, 1948 [abstr. in Chem. Abstr., v. 44, no. 19, p. 9089, 1950].

LABAYE, GEORGES, Note sur le débit solide des cours d'eau, La Houille Blanche, Spéc. no. A, 30 pp., 1948.

LITTLETON, ROBERT T., Ground-water conditions in the vicinity of Gillette, Wyoming (with a section on the quality of ground waters by SWENSON, HERBERT A.), U. S. Geol. Surv. Circ. 76, 43 pp., Oct. 1950.

LITTLETON, ROBERT T., Reconnaissance of the geology and ground-water hydrology of the Laramie Basin, Wyoming, with special reference to the Laramie and Little Laramie River Valleys, U. S. Geol. Surv. Circ. 80, 37 pp., Nov. 1950.

LULL, H. M., and MUNNS, E. N., Effect of land use practices on ground water, J. Soil and Water Cons., v. 5, no. 4, pt. 1, pp. 169-179, Oct. 1950.

LUPTON, FRANTZ R., Use of inflow forecasts in operation of Hoover Dam and Lake Mead for flood control, Western Snow Conf., Boulder City, Nevada, pp. 35-48, April 1950.

MARTIN, PIERRE, Études hydrologiques et assèchement du sud-ouest Malgache, Rev. Géogr. Alpine, v. 38, pp. 357-360, 1950.

MICHAUD, JEAN, Emploi de marques dans l'étude des mouvements du sol, Rev. Geomorph. Dyn., v. 1, no. 4, pp. 180-189, 1950.

MORTIMER, C. H., Underwater "soils", a review of lake sediments, J. Soil Sci., v. 1, no. 1, pp. 63-73, March 1949.

MUNDORFF, M. J., Flood-plain deposits of North Carolina Piedmont and mountain streams as a possible source of ground-water supply, N. C. Dept. of Cons. and Dev., Div. Min. Res., Bull. 59, 20 pp., 1950.

MUNGER, EDWIN S., Water problems of Kitui District, Kenya, Geogr. Rev., pp. 575-582, October 1950.

PARDÉ, M., Hydrologie Syrienne et Libanaise, Rev. Géogr. Alpine, v. 38, pp. 707-712, 1950.

PARDÉ, MAURICE, Les variations fluviales saisonnières dans le bassin du Mississipi, Ann. Géogr., no. 316, pp. 274-282, 1950.

PARDÉ, MAURICE, L'abondance fluviale dans le bassin du Mississipi, Ann. Geogr., v. 39, no. 315, pp. 194-202, 1950.

PAVER, G. L., The geophysical interpretation of underground water supplies; a geological analysis of observed resistivity data, J. Inst. Water Engrs., v. 4, pp. 237-266, 1950.

RÉMÉNIÉRAS, GASTON, and JEAN BOYER, Monographie hydrologique du bassin de la Maronne, pt. 2, Étude des débits, La Houille Blanche, v. 5, no. 4, pp. 441-465, 1950.

SCHAEFER, VINCENT J., A new method for studying the structure of glacier ice, J. Glac., v. 1, no. 8, pp. 441-442, 1950.

SEGERSTROM, KENNETH, Erosion studies at Parícutin, State of Michoacán, Mexico, U. S. Geol. Surv. Bull. 965-A, 164 pp., 1950.

SHEPHERD, E. M., Some factors in the hydrology of Queensland, Proc. R. S. Queensland, 1948, v. 60, pp. 3-23, Jan. 1950.

SIKÓ, A., Seepage of subsoil water around sheet piles, Hungarian Water Board, no. 3-4, pp. 231-245, 1949 (in Hungarian with summary in English).

SINGH, HARBANS, Roundness and sphericity as used in analyses of sand particles, J. Central Bd. Irrig., v. 7, pp. 163-173, March 1950

SMITH, H. F., Ground-water resources in Champaign County, Illinois, Ill. Water Surv., Rep. Investigation no. 6, 44 pp., 1950.

STALLMAN, ROBERT W., and FRED H. KLAER, JR., Ground-water resources of Noble County, Indiana, Ind. Dept. Cons., Div. Water Res., Bull. 5, 103 pp. + 5 maps, 1950.

STRAUSS, FRED A., A revision of forecasting methods as practiced by California Cooperative Snow Surveys, Western Snow Conf., Boulder City, Nevada, pp. 49-59, April 1950.
SWITHINBANK, CHARLES, The origin of dirt cones on glaciers, J. Glac., v. 1, no. 8, pp. 461-465, 1950.
TEXAS BOARD OF WATER ENGINEERS, Chemical composition of Texas surface water, 1949, 67 pp., Oct. 1950.
THOMPSON, REGINALD W. S., The application of statistical methods in the determination of the yield of a catchment from runoff data, J. Inst. Water Eng., v. 4, no. 5, pp. 394-432, Aug. 1950.
TRICART, J., and R. SCHAEFFER, L'indice d'émousse des galets, moyen d'étude des systèmes d'érosion, Rev. Géomorph. Dyn., no. 4, v. 1, pp. 151-178, 1950.
WHITE, W. F., and C. F. LINDHOLM, Water resources investigations relating to the Schuylkill River restoration project, Oct. 1947 - December 1949, U. S. Dept. Interior, Geol. Surv., Harrisburg, Pa., 125 pp., 1950.
YATEN, E., Ground water of Naka upland in Hitachi Province, Geogr. Rev., Japan, v. 23, no. 6, pp. 8-12, 1950 (in Japanese).

BIBLIOGRAPHY: TECTONOPHYSICS

ACKERMANN, ERNST, Ein neuer Faltengürtel in Nordrhodesien und seine tektonische Stellung im Afrikanischen Grundgebirge, Geol. Rundschau, v. 38, no. 1, pp. 24-39, 1950.
BHIMASENACHAR, J., Elastic constants of some cubic nitrates, Proc. Nat. Inst. Sci. India, v. 16, no. 4, pp. 235-240, 1950.
BHIMASENACHAR, J., Elastic constants of corundum, Proc. Nat. Inst. Sci. India, v. 16, no. 4, pp. 241-243, 1950.
CLOOS, ERNST, The geology of the South Mountain anticlinorium, Maryland, Johns Hopkins Univ. Studies, Geol., no. 16, pt. 1, pp. 1-28, 1950.
CLOOS, ERNST, and J. L. ANDERSON, The geology of Bear Island, Potomac River, Maryland, Johns Hopkins Univ. Studies, Geol., no. 16, pt. 2, pp. 1-13, 1950.
EDELMAN, NILS, Structural history of the eastern part of the Gullkrona basin, SW-Finland, Comm. Géol. Finlande, Bull. 148, 48 pp., 1949.
FALKE, H., Spezialtektonik am Nordrande der Nahemulde, Zs. Deutsch. Geol. Gesellschaft, v. 101, pt. 1, pp. 59-69, 1949, 1950.
GLANGEAUD, L., and D. SCHNEEGANS, Caractères généraux du style jurassien (et des types comtois el hauljurassien), Soc. géol. Belgique, v. 73, pp. 131-146, 1949-1950.
GLANGEAUD, LOUIS, Le role du socle dans la tectonique du Jura, Soc. géol. Belgique, v. 73, pp. 57-120, 1949-1950.
HÄRME, MAUNI, On the stratigraphical and structural geology of the Kemi area, northern Finland, Comm. géol. Finlande, Bull. 147, 60 pp., 1949.
HÄRME, M., and J. SEITSAARI, On the structure of a tilted dome near Tampere in southwestern Finland, Comm. géol. Finlande, Bull. 150, pp. 19-22, 1950.
HUGHES, D. S., and H. J. JONES, Variation of elastic moduli of igneous rocks with pressure and temperature, Bull. Geol. Soc. Amer., v. 61, pp. 843-856, 1950.
KRAUS, E., Über geotektonische "Leitlinien", Zs. Deutsch. geol. Gesellschaft, v. 101, pt. 1, pp. 9-22, 1949-1950.
LÉBANON, MINISTÈRE DE TRAVAUX PUBLICS, Carte Geologique, Feuille de Saida (notice explicative) Beyrouth, pp. 1-45, 1949.
LUCIUS, M., Das Oesling, Pub. Service geol. Luxembourg, v. 6, 1950.
MARTIN, HENNO, Sudwest-Afrika, Geol. Rundschau, v. 38, no. 1, pp. 6-14, 1950.
MATSCHINSKI, M., The formation of continents and geodynamic forces, C.-R. Acad. Sci., Paris, v. 230, pp. 1882-1884, 1950 (in French) [abstr. in Physics Abstracts, v. 53, no. 634, p. 872, 1950].
MIYASHIRO, AKIHO, The stability relation of kyanite, sillimanite, and andalusite, and the physical conditions of the metamorphic processes, J. Geol. Soc. Japan, v. 60, no. 650-651, pp. 218-223, 1949.
MIYASHIRO, AKIHO, A note on "stress-minerals", J. Geol. Soc. Japan, v. 60, no. 650-651, pp. 211-217, 1949.
SANDER, BRUNO, Einführung in die Gefügekunde der geologischen Körper; pt. 2, Die Korngefüge, Springer, Wien und Insbruck, 409 pp., 1950.
PILGER, ANDREAS, Die tektonischen Probleme des initialen Magmatismus, Geol. Jb., v. 65, pp. 1-30, 1950.
SCHMIDT-THOMÉ, PAUL, Geologie des Isartalgebietes im Bereich des Rissbach-Stallens und des geplanten sylvenstein-Staubeckens, Geologica Bavarica, no. 4, 55 pp., 1950.
U. S. BUREAU OF RECLAMATION, An analysis of the stress distributions in and near stress gages embedded in elastic solids, Structural Res. Lab. rep. SP-26, 42 pp., 1950 (processed).

VENING MEINESZ, F. A., Les graben africains, résultat de compression ou de tension dans la croûte terrestre?, Bull. Séances, Inst. R. Col. Belge, v. 21, no. 2, pp. 539-552, 1950.
ZÖLLNER, WALTER, Observaciones tectonicas en la Precordillera Sanjuanina, Zona de Barreal, Rev. Assn. Geol. Argentina, v. 5, no. 3, pp. 111-126, 1950.

NOTES AND PERSONALIA

NOTES

Corrigendum--In the issue of October 1950, Figure 4 in the paper of Wiegel and Kimberley, p. 720, the title "Chromatic charts. . ." should read "Climatic charts. . ." as they relate to the frequency and direction of strong winds.

Protection of technical information--The Office of Technical Services in the Department of Commerce has provided a service to advise organizations and individuals whether or not it would be harmful to the national welfare to release technical information. Sometimes information secured from a number of persons or organizations may be pieced together to become information that might be harmful. While this does not fall within formal security regulations, the aid of the public is enlisted on a voluntary basis. Requests for advice concerning release of technical information, together with manuscripts, plans, or documents, should be sent to the Office of Technical Services, U. S. Department of Commerce, Washington 25, D. C.

New magnetic observatory at the University of Houston--Through the cooperation of the University of Houston, the Ruska Instrument Company, and the U. S. Coast and Geodetic Survey, a new magnetic observatory was recently established at the University of Houston. This is the third such observatory in the United States; the other two are the observatories of the U. S. Coast and Geodetic Survey at Cheltenham, Maryland, and at Tucson, Arizona. The University of Houston furnished the site and the two small non-magnetic buildings, and is operating the station under the auspices of the Coast and Geodetic Survey. The instruments were built and donated by the Ruska Instrument Company.

New soil moisture meter--A patent has been granted to E. A. Colman of the California Forest and Range Experiment Station of the U. S. Forest Service for a new soil moisture meter which can be used to determine the direction and rate of water movement in soils, the detection of freezing and melting, and other studies. The patent has been assigned to the United States Government. The instrument consists of two electrodes of monel metal screen, separated by fiberglas fabric, and encased in a perforated monel metal envelope. It is buried in the soil, and is connected to an ohmmeter for the measurement of electrical resistance, which is related to the moisture content. The meter has a range from air-dryness to saturation. Three thousand units are now in use throughout the world.

Bulletin reporting instrumental seismic readings--The Standing Committee on Seismology of the Pacific Science Association has prepared a check list of current bulletins reporting instrumental seismic readings, including general bulletins and those from countries of the Pacific region. Copies of the list may be secured from the Chairman of the Committee, Charles F. Richter, Seismological Laboratory, 220 N. San Raphael Ave., Pasadena, Calif., U.S.A.

Meetings on carboniferous stratigraphy and on sedimentology to be held in Holland--The Third Meeting on Carboniferous Stratigraphy, called by the Geologische Stichting, and the Geologisch Bureau v. h. Mijngebied of The Netherlands, is to be held at Heerlen, June 25-30, 1951. Its main purpose is to renew and strengthen relations between coal-measures geologists and palaeontologists of the various nations, and to exchange information on progress since the Second Meeting in 1935. After the meetings there will be visits to collories and elsewhere which will cover the interval until the meeting on sedimentology to be held July 4-14 at Wageningen and Groningen. With regard to the former meeting, interested persons should write to the Geological Bureau, Postbus 126, Heerlen, The Netherlands; and with regard to the latter to Dr. D. J. Doeglas, Wageningen, The Netherlands.

Graduate assistantships in meteorology and climatology at Florida State University--Announcement has been made of the availability of graduate assistantships in meteorology and climatology at Florida State University carrying stipends of $125 per month. Appointments will be made in connection with research projects being conducted for the Office of Naval Research and the Air Materiel Command, U. S. Air Force. Non-resident tuition fees for non-resident students are forgiven, and a student may carry as many as ten hours of work toward his advanced degree. Applications should be filed before May 1, 1951. Further information may be secured through the Dean of the Graduate School of the University, Tallahassee, Florida.

Two new graduate courses in geodetic engineering at the University of Illinois--Two new graduate courses in geodetic engineering have been established in the Civil Engineering Department of the University of Illinois. One of these deals with the principles and practice of precise triangulation, traverse, and levels, and the other with the astronomic determination of position and direction, systems of plane coordinates, map projections, and electronic and other special control surveys. Inquiries concerning these courses should be addressed to Milton O. Schmidt, Associate Professor of Civil Engineering at the University, Urbana, Illinois.

Mineral Symposium at Emory University--A Southeastern Mineral Symposium will be held at Emory University, Atlanta, Georgia, March 29-31, 1951. A two-day session on geological problems will be followed by field trips. Persons who are interested should get into touch with Arthur C. Munyan, Department of Geology at Emory University.

Scientific Radio Union Meeting--The regular joint spring meeting of the National Committee of the United States, International Scientific Radio Union (URSI), and the Professional Group on Antennas and Wave Propagation, Institute of Radio Engineers, will be held at the National Bureau of Standards in Washington, D. C., April 16-18, 1951. Sessions will be held by the URSI Commissions on Tropospheric Radio Propagation, Ionospheric Radio Propagation, Terrestrial Radio Noise, and Radio Waves and Circuits. For further information, write to Newbern Smith, who is Secretary of the National Committee, URSI, at the National Bureau of Standards, Washington 25, D. C.

Centenary volume of the Royal Meteorological Society--A special Centenary Volume including the papers of the Centenary Meeting in Oxford and London in 1950 is now available through the Royal Meteorological Society, 49 Cromwell Road, London, S.W. 7, England. The volume contains about 300 pages with subjects ranging over most of the field of meteorology. The price is £1.1.6, including postage.

New Japanese publication in geophysics--The Meteorological Research Institute of Tokyo has released volume 1, number 1, of the publication Papers in Meteorology and Geophysics, dated October 1950. The Meteorological Research Institute is a branch of the Central Meteorological Observatory located in Tokyo, and has seven constituent laboratories: Forecast Research, Aerological, Weather Instruments, Physical Meteorological, Applied Meteorology, Geochemical, and Geoelectric and Geomagnetic. It is planned to publish the new journal quarterly. Some of the bibliographic entries from this number appear in the bibliography of this issue; others will appear in April.

ZiKaWei and ZoCe observatories taken over by Chinese--A Chinese military group, led by the President of the Academia Sinica, seized the two private observatories of ZiKaWei and ZoCe near Shanghai, without warning in December 1950. These had been operated by the Catholic French Mission, and, during the war with Japan, had sheltered the best instruments of the Academia Sinica. The ZiKaWei Observatory, over 75 years old, included modern meteorological equipment which had been of special service with regard to typhoons. It also included seven seismographs, a radio radar meteorological research laboratory, a high-precision time-signaling station connected with the international study of longitudes, and a substantial library. The ZoCe Astronomical Observatory had a double 40-cm refractor with photographic and spectroscopic equipment, equipment for the measurement of solar radiation, a modern magnetic department, and an excellent library. The value of the observatories and their equipment is probably in the neighborhood of a million dollars. The staff was forced to leave, leaving most of their personal belongings and notes behind. No citizen of the United States was or had ever been a member of the staff. It is suggested that exchange publications, formerly sent to either of these observatories, now be sent to Macau Observatory, Capitania, Macau, via Hongkong.

PERSONALIA

A. E. Berndes, Jr. has left the Texas Company after 14 years of service and is now associated with the Interphone Electric Company in Los Angeles.

Howard T. Odum, who recently took his degree of Doctor of Philosophy in Zoology at Yale University, is now Assistant Professor of Biology at the University of Florida.

Leon Herman, on leave from the Astrophysics Section of the Observatory of Paris, is now serving as a Visiting Research Fellow at the Geophysical Institute of the University of Alaska on a Fulbright scholarship. He is studying aurora, twilight, and airglow.

Milton O. Schmidt, Associate Professor of Civil Engineering of the University of Illinois and Manager of the University's Summer Surveying Camp, took his degree of Doctor of Philosophy at the University in October 1950.

Samuel Shulits, formerly Deputy Chief, Plans and International Affairs Section, Transport Group, Bipartite Control Office in Germany, has accepted a position as Assistant Professor of Civil Engineering at Michigan College of Mining and Technology.

Theodore von Karman, Chairman of the Scientific Advisory Board, U. S. Air Force, has been awarded the Kelvin Gold Medal for 1950. He is the second citizen of the United States to receive the Medal.

Dean C. Wellman is now manager of the recently-opened Denver office of the Derby Oil Company.

Philip H. Williamson, Mathematician of the Geomagnetism Branch of the U. S. Coast and Geodetic Survey, recently retired and has taken up residence in Baltimore. He entered the Survey in 1907, spent ten years of service in the Philippine Islands and nearly 17 years in the Washington office. During World War II, he headed a special group compiling magnetic charts for the Armed Forces.

Thomas Arthur Blair, retired, in residence at La Jolla, California, died September 29, 1950 at the age of 71. He received his baccalaureate degree from Stanford University in 1907, and entered the service of the U. S. Weather Bureau at that time, serving in numerous locations, including Lincoln, Nebraska, where he served the Bureau and the University of Nebraska as Professor of Meteorology at the same time from 1924 until his retirement in 1943. His particular field of study concerned the correlation of weather to wheat yields, temperature correlations, and seasonal pressure anomalies, and he wrote a book, Weather Elements, the third edition of which was published in 1948. He had been a member of AGU since 1930.

Norman E. Hawes, Forester with the U. S. Forest Service at Upper Darby, Pennsylvania, died April 16, 1950 at the age of 44. He was born in Boston, Massachusetts, and took his baccalaureate degree from Washington and Lee in 1929, and his degree of Master of Forestry from Yale in 1932. He was a member of the Yale Botanical Expedition to the West Indies, and entered the Federal service on forestry work in 1933. He was engaged in research work on forest influences for the Forest Service in various locations--Virginia, the Ozarks, Mississippi, and Georgia--before taking up duties in Pennsylvania. He had been a member of AGU since 1943.

William Ferdinand Petersen, pathologist, and Director of Clinical Research at St. Luke's Hospital in Chicago, died August 20, 1950 at the age of 63. He was born in Chicago and received his baccalaureate degree from the University of Chicago in 1909, and his Doctor of Medicine from Rush Medical College in 1912, following which he took advanced work at Harvard and Columbia. He served at Vanderbilt from 1914 to 1917, and the University of Illinois from 1919 to 1943. He became Director of Clinical Research at St. Luke's in 1947. His broad interests in medicine brought him into geophysics, chiefly through meteorology. He was author of many medical writings, including (with Margaret E. Milliken) The Patient and the Weather. He had been a member of AGU since 1948.

Leland Bradley Snoddy, Professor of Physics at the University of Virginia, died November 12, 1950 at the age of 52. He was born in Hiram, Ohio, received his baccalaureate degree from the University of Kentucky in 1921, his Master of Arts degree from the same school in 1923, attended the University of California from 1923 to 1925, and took his doctorate in physics from the University of Virginia in 1929. He served as Professor of Physics at Lynchburg College from 1925 to 1928. He had been on the staff of the University of Virginia since 1928, except for the war period 1940 to 1945, when he served the Office of Scientific Research and Development. His special field of study was in electric arc discharges and the separation of isotopes by centrifugal means. He had been a member of AGU since 1939.

MINUTES OF EXECUTIVE COMMITTEE MEETING, AMERICAN GEOPHYSICAL UNION

Meeting of November 15, 1950

The meeting was called to order at 13h 30m in the Board Room of the National Research Council - National Academy of Sciences Building, 2101 Constitution Avenue, Washington, D. C., by President Walter H. Bucher.

Present--Thirty-one persons were present, namely: L. H. Adams, L. R. Alldredge, Robert Balk, K. Hilding Beij, Walter H. Bucher, Wilbur S. Burbank, Perry Byerly, Horace R. Byers, Felix Chayes, H. N. Eaton, Jno. A. Fleming, Harry H. Hess, A. J. Hoskinson, Earl Ingerson, Woodrow C. Jacobs, J. Wallace Joyce, Walter D. Lambert, Walter B. Langbein, Esper S. Larsen, Jr., James B. Macelwane, John Putnam Marble, Leonard M. Murphy, Mary C. Rabbitt, F. W. Reichelderfer, Roger R. Revelle, Irwin Roman, McClain B. Smith, Waldo E. Smith, Victor Vacquier, James T. Wilson, and George P. Woollard.

Absent--The following were excused: Roger Adams, Fred Anderegg, Merrill Bernard, Francis Birch, J. A. B. Bjerknes, Ralph E. Cleland, Ernst Cloos, H. W. Hemple, M. King Hubbert, C. E. Jacob, Ray K. Linsley, Martin A. Mason, George F. McEwen, Alfred C. Redfield, Harlan T. Stetson, F. J. Veihmeyer (Walter B. Langbein attended as alternate), Hurd C. Willett, and Howell Williams.

Approval of Minutes--The minutes of the meeting of May 3, 1950 were approved as published in the August, 1950 issue of the Transactions, pages 636 to 649.

General Secretary's Report

General Activities

Executive Committee--There have been extensive changes in our Executive Committee as a result of the elections and the appointment of new committees for the current triennium. In addition to these changes, the representatives on our Executive Committee from the National Research Council have been changed by the appointment of Douglas Whitaker of Stanford University as Chairman of the National Research Council and the appointment of Roger Adams of the University of Illinois as the new Chairman of the Division of Foreign Relations of the National Research Council. The other new members of the Committee are as follows: L. R. Alldredge, Secretary, Terrestrial Magnetism and Electricity; Robert Balk, President, Tectonophysics; Perry Byerly, President, Seismology; Felix Chayes, Secretary, Volcanology; Morgan D. Dubrow, Chairman, Committee on Membership; Harry H. Hess, President, Geodesy; Benjamin Holzman, President, Meteorology; Esper S. Larsen, Jr., President, Volcanology; A. C. Redfield, President, Oceanography; Frank J. Veihmeyer, President, Hydrology; R. Hansen Weightman, Chairman, Committee on Audit; and James T. Wilson, Secretary, Seismology.

Most of the Committees of the Union are now complete. They are listed in the Directory of the Members published as Part 2 of the October 1950 issue of the Transactions. Since that date there has been one addition to the Membership Committee representing the Section of Tectonophysics (Aaron C. Waters); two additions to the Committee on Meetings (Walter E. A. Ruska and Glenn E. Stout); and the Committee on Resolutions has been appointed (Mary C. Rabbitt, Chairman; Werner A. Baum, and Francis G. Wells).

Financial Report--A detailed financial statement, prepared as of June 30, 1950, has been approved by the Committee on Audit. As of November 1, 1950, our total liquid assets were $11,351.09, including the Permanent Fund of $3,202.55, the Robert E. Horton Fund of $1,180.91, the William Bowie Medal Fund of $107.90, and a cash reserve of $6,859.73. This compares with a total of $7,995.89 on November 1 a year ago, including $5,227.89 in the cash reserve and $2,938 in the Permanent Fund. The difference ($3,185.20) reflects the increase in dues payments directly and indicates that we will probably close our fiscal year without deficit.

Membership--A new Membership Committee has been appointed and is now in the process of organization. Work has been carried on during the intervening months by members of the Committee, resulting in a gross addition of 231 members. Also there are about 40 applications in hand. A statement for the period since our last meeting is as follows:

Membership, April 28, 1950	4,595	
New members, April 28 to November 10, 1950	231	4,826
Resignations	64	
Deceased	9	
Inactive	1	
Dropped	107	181
Membership, November 10, 1950		4,645

Those dropped include 12 who were elected to membership but who never paid dues, and 95 who were among the 114 cited at our last meeting, recommended to be dropped for non-payment of dues. The figure of 4,645 hardly represents the net membership because there is a larger number who have not paid this year than last, and it is probable that there will be a larger group ultimately to be dropped. At the present time there are 197 who have not paid dues for 1949 and 1950, and 454 who have not yet paid dues for 1950. These figures compare with 122 a year ago who had not paid their 1948 and 1949 dues (most of whom were dropped as cited above) and 333 who had not paid dues for 1949.

Our net paid membership since the beginning of this year is about 35 less than last year at this time. This is believed to be due in major part to the increase in dues, but as cited by the Committee on Audit the dues receipts for the year ending June 30, 1950 were 35 per cent higher than in the preceding year.

Nine deaths have been reported since our meeting of May 3. These are as follows: P. G. Nutting, August 8, 1949; Chas. N. Gould, August 13, 1949; Herbert J. Swasey, Jr., October 18, 1949; H. Shaw, May 4, 1950; Albert K. Ludy, June 10, 1950; Norman R. Beers, June 27, 1950; Chas. J. Hubbard, July 31, 1950; Kirk Bryan, August 22, 1950; and Wm. A. Orr, August 23, 1950.

We now have 44 life members, nine through payment of $100 each and the balance by other statutory provisions.

There have been two additional requests for certificates of membership in the American Geophysical Union suitable for framing.

Corporation Membership--We have added one Corporation Member since our last meeting, this being the welcome addition of the Institute of Geophysics of the University of California. We have indication of one resignation.

Meetings--The Thirty-Second Annual Meeting is scheduled to be held in Washington April 30 to May 2, 1951.

The Twenty-Sixth Regional Meeting is scheduled to be held in Fresno, California, February 9 and 10, 1951. The Section of Hydrology is proceeding with plans and is being joined by the Section of Meteorology. Arch R. Addington, Chairman of the Department of Geology and Geography of Fresno State College, has been designated Chairman for this meeting with A. A. Lothman, in charge of the office of the Weather Bureau at Fresno, as a member of the Committee, with authority for the Chairman to co-opt others.

The Union was invited to join the Western Snow Conference in a meeting in Victoria, British Columbia, on April 19 and 20, 1951, but all Sections decided not to accept.

Publications--Beginning July 1, 1950, we decreased the edition from 5,200 to 5,000 for the remainder of the current year. This has been done for two reasons, first, those who have not paid dues for the current year are carried to July, following which date their subscriptions are suspended. In past years we have found that as a result our stock of Transactions for the last half of the year is 150 to 200 more than for the first half of the year. The second reason is the increase in the number who have not paid dues this year as compared with last.

The work is progressing on the indexing of the first 25 years of the Transactions, this matter now being in the hands of Miss Marjorie Hooker of the U. S. Geological Survey who expects to

complete the work preparatory to setting up the master copy by the end of 1950.

There is to be a meeting of the editors of periodicals carrying material of interest to geologists on November 17 in connection with the meeting of the Geological Society of America. The Chairman and Secretary of our Editorial and Publication Committee plan to be in attendance. This is in the interest of attempting to unify standards of presentation.

The ultimate disposition of the exhibit maps prepared by W. T. Thom and George P. Woollard in connection with the General Assembly of IUGG in 1939 should be considered. There is still an occasional order for prints, but we are advised that the maps are being redrawn and being brought up to date in some instances. It would seem that the usefulness of some of the maps does not warrant their retention. Suggestions and recommendations will be appreciated.

Administration of the Union--Our present arrangements for space in the Administration Building of the Carnegie Institution of Washington expire at the end of January, 1951, and prior to that date the administrative officers of the Union will request for the continuance of the present space allotment, at the same time keeping our parent organization, the National Research Council, advised of our needs.

Personnel--The personnel continues as of May, 1950 with Samuel Pepper as the Secretary-Stenographer, Mrs. Geraldine L. Lamb as Editorial Assistant and Electromatic Operator, and Mrs. Ida A. Edwards and Miss Hilda A. Borgos as Clerk Typists.

Affiliation with the American Association for the Advancement of Science--A year ago the Executive Committee considered the matter of affiliation with the American Association for the Advancement of Science, and charged the officers of the Union with the responsibility of investigating what might be given, what might be the benefits, and what might be the ultimate course of such association. This has been done and recommendation is made that we should affiliate, even though it is not possible to cite specific contributions or benefits or the future course. There is something definite to be contributed by AGU to the AAAS in that geophysics is one of the voids in their organization embracing, as it attempts to do, all the fields of science. On the other hand, the AAAS offers to be of aid in the organization of meetings, and in any meeting which they hold AGU would be invited to organize such sessions as seem desirable. As to the future course, judging from the past it is just a matter of general support to an integrating science endeavor and the course that this holds for AGU may be largely guided by our own desires.

American Standards Association--At the present time the AGU has representation on the American Standards Association Committee on Photography Z38. This has been of long standing and Fred Anderegg is our representative. This Committee, which has now become very large, will probably be divided into four, in which case AGU will presumably be affiliated with the Committee on Photographic Sensitometry if this is desired. The situation is somewhat uncertain at present, but continuance of representation seems to be desirable.

AGU is also represented on the Committee on Permeability Z59, C. E. Jacob being our representative and Chairman of the Committee which was organized on the recommendation of the Geological Society of America and the American Geophysical Union.

An offer has come from the American Standards Association to be represented on the Committee on Graphical Presentation Z15. While this is not a matter of major concern in geophysics, graphical presentation is important just as is photography. Comments on such representation are invited.

National Mobilization of Scientific Manpower--The international situation became such that the officers of the Sections were alerted by President Bucher in August in case need should arise for the services of geophysical scientists with particular qualifications. A second letter was sent out in October relative to developments up to that time and the establishment of a National Register, outlining that we would be called upon both by the National Research Council and the American Geological Institute for aid. A call from the Council came shortly afterwards in connection with the establishment of a check list for the geophysical sciences based upon a functional outlook. Responses from offices and organizations were gratifying and a tentative check list has been completed.

Education in Geophysics--In 1945, on the instigation of the National Roster, AGU undertook a survey of education in geophysics following which a report under that heading was published in the

December, 1945 issue of the Transactions, with an addendum in August, 1946. This has served a very useful purpose and requests for copies of the reprint are still being received. However, it was rather incomplete, and is now out of date. There has been some thought that this survey should be repeated on a more comprehensive basis, and to this end we have sought support from the Research and Development Board and the Air Force. Both of these have advised that such a survey is not within their prerogatives. Here the matter rests and the question is raised whether or not we should take steps to remake this survey and, if so, what support we might secure to do this job comprehensively.

Visual Aids--Need also arises from time to time for material relating to visual aids in teaching. Many schools are attempting to do more work in geophysics. We should try to be of aid in this connection. Perhaps a survey of the visual material available for the teaching of geophysics, both cinema film and slides, should be made. This project has not progressed for lack of staff time, but comments and recommendations concerning such a project are invited.

News Items--The Pan American Institute of Geography and History held its Fifth General Assembly in Santiago, Chile, October 16-27, 1950. The AGU was invited to send a representative and Elliott B. Roberts of the U. S. Coast and Geodetic Survey was designated by President Bucher.

The AGU was invited to send a representative to the Diamond Jubilee Celebration of Brigham Young University at Provo, Utah. Walter M. Elsasser, Professor of the Department of Physics of the University of Utah in Salt Lake City, was designated.

The AGU was also invited to designate a representative to the inauguration ceremony of the new President of the Utah State Agricultural College at Logan, Utah. Willard Gardner was invited to act as our representative, but our letter found him in Iowa too late for such designation. The College authorities were written appropriately.

Responses have been received from a number of resolutions that have been sent out. All resolutions have gone forward excepting Resolution Six relating to the British Antarctic Expedition, which is awaiting word of the proper recipient.

We continue to send bibliographic material received on exchange to the Library of Congress. Acknowledgment from the Library of over 600 items in the past year has been received.

Activities as Committee on Geophysics of the National Research Council

National Research Council--The National Research Council has made a grant of $400 available for the work of AGU for the current year.

There have been no changes in our appointments to Council Divisions and other organizations, W. T. Thom, Jr. continuing as AGU representative in the Division of Geology and Geography, and W. T. Thom, Jr. and George P. Woollard remaining as our Directors on the Board of the American Geological Institute.

On July 1, 1950 the National Academy of Sciences adopted a health and insurance plan under which its participating staff members have the benefit of membership in Group Hospitalization, Surgical Service Plan, and a term life insurance policy. The American Geophysical Union, as part of the National Research Council, was invited to participate in this plan and four of our five staff members are now covered.

International Union of Geodesy and Geophysics--The International Association of Scientific Hydrology is urging the various National Committees to revive their projects on the bibliography of hydrology, and complete these as soon as possible for the years 1941 to 1950, inclusive. Our plan for accomplishing this involves a contract between the Department of the Interior (supported by six or eight other agencies) and the National Research Council under which the American Geophysical Union will undertake to prepare the copy for this job. The National Research Council will engage Ray K. Linsley, on the President's recommendation, to make the compilation, following which copy will be turned over to the office of AGU for processing. Final publication, it is planned, will be by the Bureau of Reclamation. A limited number of copies will be supplied for the International Association of Scientific Hydrology, and to the American Geophysical Union for limited distribution.

A colloquium on Plastic Flow and Deformation within the Earth was held in Hershey, Pennsyl-

vania, on September 12, 13, and 14 under the auspices of the International Union of Geodesy and Geophysics and the International Union of Theoretical and Applied Mechanics, attended by about 25 scientists in the United States and abroad. L. H. Adams, Secretary of the Organizing Commission, will report on this later.

A. Letroye, Vice-President of the Belgian Organizing Committee for the Ninth General Assembly of the IUGG to be held in Brussels August 21 to September 1, 1951, was in the United States in the late spring and outlined plans thus far developed for the meeting. This was reported in the June 1950 issue of the Transactions, page 493. Little additional information has been received since, excepting that plans are progressing. The formal invitation has not yet been received, but at the time of the meeting with Letroye there was the thought that the formal invitation might not be forthcoming until the winter. We have carried an announcement of this meeting in each recent issue of the Transactions, requesting those who planned to attend to advise the office of AGU so that they may be kept informed.

There is a plan on foot to reorganize the International Union of Geodesy and Geophysics. Three different plans have been proposed. It would seem appropriate that we should study these plans and be in a position to offer suggestions by the time of our meeting next spring in order that proper representations may be made and the American delegation instructed.

F. Signore, Secretary of the International Association of Volcanology, has informed us that he has 300 sets (two volumes each) relating to the Washington Assembly reserved for the United States at a cost of $3 per volume. In view of the money involved and the uncertainties as to obligations of the Union, suggestions and recommendations are requested.

K. Hilding Beij
General Secretary

Action on the General Secretary's Report--The report was accepted.

International Matters--J. A. Fleming reported that the State Department has paid U. S. dues ($2240) to IUGG for 1950. He advised also that a new International Union of Physiology is being considered, and that a movement is under way to reestablish the International Union of Mathematics. There is some discussion that the International Council of Scientific Unions may hold a three-day session in Washington, D. C., some time in October, 1951. The National Research Council has offered the use of facilities. Such a meeting would serve to permit scientists in the United States to become better acquainted with the work of the Council. He also advised that the State Department has indicated that it plans to send six delegates to the meeting of the International Astronomical Union to its General Assembly in Leningrad in 1951.

L. H. Adams reported briefly on the Colloquium on Plastic Flow and Deformation within the Earth held at Hershey, Pennsylvania, in September, 1950, as set forth in Appendix 1.

Harry H. Hess, recently returned from South Africa, reported briefly on developments in geophysics in that region, noting the successful use of seismic methods of exploration in the location of gold ore. Work is being done in the study of seismic waves through rock bursts. Bernard Price Institute in Johannesburg has been set up to promote geophysics in South Africa. About 6000 gravimetric observations, mostly commercial, are available to the government, and the Geological Survey of South Africa is starting gravimetric work. A new ship Africaner II, for biological oceanographic work is in operation, but little is being done as yet in physical oceanography other than soundings. The Union government has refitted the Protea as a hydrographic survey ship. With the work in progress in meteorology and hydrology, he was not familiar.

Reports of Standing Committees

Meetings--Chairman Marble announced that plans are progressing for the Twenty-Sixth Regional Meeting to be held in Fresno, California, February 9-10, 1951. The meeting was initiated by the Section of Hydrology, with the likelihood that Meteorology will join. Plans are likewise developing well for the Thirty-Second Annual Meeting which will be held in Washington, D. C., April 30-May 2, 1951. It is planned that there shall be one or two symposia.

Audit--Chairman Weightman presented the report of the Committee on Audit for the fiscal year ending June 30, 1950 [Trans. v. 31, Dec. 1950, pp. 955-957]. The report was accepted.

Reports of Special Committees

Student Membership and Student Chapters--The report of this Committee received by the Executive Committee on May 3, 1950 [Trans. v. 31, Aug. 1950, pp. 648-649], and referred to the Committees on Budget, Statutes and By-Laws, and Editorial and Publication. The recommendations of the Chairmen of these Committees were heard, and there was extensive discussion. It was finally voted that no steps be taken at this time to establish a student membership grade, but the General Secretary was authorized to establish a special student subscription rate to the Transactions that would defray the actual costs, such subscriptions to be on a calendar-year basis involving a certificate of the status of the student by the head of the department in which the student is majoring, subject to renewal during student status to a maximum of five years. The The maximum number for 1951 is limited to 100. (The General Secretary has established the rate as $4 for the year 1951, and letters have gone to department heads of schools offering courses in various aspects of geophysics.)

To Consider the Formation of a Section on Geochemistry and Radioactivity--Chairman Ingerson presented the report (see Appendix 2) which was received and referred to the Section of Volcanology.

Affiliation with Other Organizations

American Geological Institute--Representative Woollard advised that the American Geological Institute is considering the admission of the Association of State Geologists as one of the affiliated organizations, pointing out that this is an organization of administrators rather than scientific geologists. The matter was discussed at some length, and it was finally approved that we advise our representative directors that, while the Executive Committee favored the admission on the basis of the facts at hand, they (our representatives) were free to act as seemed to them desirable.

Unfinished Business

American Association for the Advancement of Science--Pursuant to the instructions of the meeting of the Executive Committee on October 28, 1949, the officers of AGU investigated the pros and cons of affiliation with the AAAS, and found that AGU could do a service to AAAS in extending the field of coverage of that all-science organization; that AAAS could be of service to AGU in aiding in the organization of meetings at scattered points throughout the country in connection with meetings of AAAS; and that the course of such affiliation could not be determined at this time, but could be set from time to time as desired. After discussion it was moved and approved that we affiliate.

New Business

The matter of the settlement of the account with the Association of Vulcanology, IUGG, for copies of the Association's publications relating to the Washington General Assembly of IUGG in 1939, was referred to the Committee on Budget for study and action.

The revision of "Education in Geophysics" prepared in 1945 on the basis of a survey undertaken with the encouragement of the National Roster, but at AGU expense, was considered. The survey has been found valuable but incomplete, and is now out of date, though requests still come for reprints. It was suggested that the Office of Education may have interest in aiding in this matter. Unless such aid is forthcoming, the situation should be studied further, with action deferred.

The need for an index of visual teaching aids, both cinema and slides, was discussed. It was pointed out that many organizations issue indices of their own such material, and perhaps what will be helpful is simply an index of these sources, not listing particular items.

The matter of certificates of membership has been discussed in the past, but no formal action was taken. It was voted that except for corresponding members (honorary, foreign) such certificates should not be issued because of difficulty of control.

A letter from Gail A. Hathaway, President-elect of the American Society of Civil Engineers, to our President was read. This related to the centenary of the ASCE in 1952 and the celebration that is being planned to be held in Chicago in September of that year. It pointed out that 100 years ago all engineering was divided into two parts, military and civil, and that thus this celebration related not to the Civil Engineers, as they are considered today, but to all non-military engineering.

Thus, all organizations involving the professional or the scientific and technological side of engineering are being invited to join with the ASCE in this celebration. The particular invitation related to the IUGG, requesting the AGU, as the National Committee from the USA, to invite IUGG to take part in what way it saw fit. (A similar invitation has since come to the AGU pertaining to itself, and the Committee on Meetings now has this matter under study.) It was approved that the Executive Secretary should write General Secretary Stagg of IUGG to inquire concerning IUGG interest in this.

Adjournment--Meeting adjourned at 16h 40m.

K. Hilding Beij, General Secretary
Waldo E. Smith, Executive Secretary

APPENDIX 1--COLLOQUIUM ON PLASTIC FLOW AND DEFORMATION WITHIN THE EARTH

L. H. Adams

In December 1949 the International Union of Geodesy and Geophysics and the International Union of Theoretical and Applied Mechanics resolved to organize jointly a colloquium in order to provide an opportunity for an extended discussion of plastic flow and deformation within the Earth. A Commission for organizing the colloquium was appointed by President Vening Meinesz of the IUGG and consisted of B. Gutenberg, Seismological Laboratory, Pasadena, California; F. A. Vening Meinesz, Royal Netherlands Meteorological Institute, The Netherlands; H. L. Dryden, National Advisory Committee on Aeronautics, Washington, D. C.; W. Prager, Brown University; J. M. Burgers, Secretary, International Union of Theoretical and Applied Mechanics, The Netherlands; and L. H. Adams, Geophysical Laboratory, Carnegie Institution of Washington, Washington, D. C.

L. H. Adams agreed to act as Secretary; and with the approval of the officers of IUGG he designated as a local Committee on Arrangements those members of the Commission resident in Washington, and, in addition, J. A. Fleming and M. A. Tuve, with E. G. Fullinwider as Executive. The unique feature of this meeting was to bring together scientists in the fields of both Mechanics and Geophysics for discussion of the subject as given above.

A grant for travel expenses was obtained from UNESCO. Other expenses were covered by a donation from E. L. DeGolyer of Dallas, Texas, and by support from the Department of Terrestrial Magnetism and the Geophysical Laboratory of the Carnegie Institution of Washington. Participants were limited to 24 and were divided about equally between scientists from the United States and foreign scientists. The list is as follows: L. H. Adams, Geophysical Laboratory, Carnegie Institution of Washington; Hugo Benioff, Seismological Laboratory, Pasadena, California; P. P. Bijlaard, Cornell University, New York; Francis Birch, Dunbar Laboratory, Harvard University; Walter H. Bucher, Columbia University; Edward Bullard, National Physical Laboratory, Middlesex, England; J. M. Burgers, IUTAM, Delft, The Netherlands; J. F. Cox, Free University of Brussels, Belgium; H. L. Dryden, IUTAM, Washington, D. C.; B. G. Escher, Leiden University, The Netherlands; E. G. Fullinwider, Geophysical Laboratory, Carnegie Institution of Washington; Jean Goguel, Paris, France; Louis Glangeaud, Besancon University, Doubs, France; David T. Griggs, University of California; B. Gutenberg, Seismological Laboratory, Pasadena, California; W. Heiskanen, Helsinki, Finland; H. H. Hess, Princeton University; A. Nadai, Pittsburgh, Pennsylvania; Folke K. G. Odqvist, Royal Institute of Technology, Stockholm, Sweden; W. Prager, Brown University; Wm. W. Rubey, U. S. Geological Survey; J. H. F. Umbgrove, Wassenaar, The Netherlands; F. A. Vening Meinesz, Meteorological Institute, The Netherlands; and Ernest H. Vestine, Department of Terrestrial Magnetism, Carnegie Institution of Washington.

The meeting was held at a resort hotel in Hershey, Pennsylvania, on September 12-14, 1951. Most participants assembled in Washington and drove together to Hershey. There, in quiet and attractive surroundings, they carried on discussions both in scheduled meetings and in private conversations.

Unlike most symposiums there was no fixed program and no scheduled presentations. The colloquium was opened by the Secretary who outlined the general nature and scope of the subject-matter. A chairman (called a Moderator) was designated for each meeting to preside and to guide the proceedings.

At the close B. Gutenberg was asked to give a brief summary of all the talks that had been

made in conference. This he did in a most inclusive and effective manner.

The following topics were among those discussed: (1) Basic concepts and terms in the mechanics of deformable substances, and results of experiments on the deformation of marble, alabaster, and other substances under high pressure; (2) What is the geological evidence for motion within the Earth? (3) Deformation of the Earth's crust in geosynclines; (4) Folding and buckling of rock formations; (5) Mechanics of convection currents in the earth; (6) Sub-crustal currents and movements of the continents; (7) Plastic properties observed in geological processes (postglacial uplift isostasy) and in earthquakes; (8) Magnetic effects; (9) Seismic implications; (10) Isostasy; and (11) Properties and behavior of crustal materials under various stress systems.

At the conclusion it was decided that a summary of essential discussions would be of definite value. Participants were invited to submit a synopsis of their own remarks and a committee was appointed to edit these and prepare the review. Gutenberg consented to head this committee. He is assisted by Burgers, Benioff, and Griggs.

The Secretary has received letters from the participants indicating that the objectives of the colloquium were attained to a most gratifying extent. To quote one, "It did more to focus my thinking on fundamental concepts than almost any other meeting I have attended...."

APPENDIX 2--REPORT OF THE COMMITTEE TO CONSIDER THE FORMATION OF A SECTION OF GEOCHEMISTRY AND RADIOACTIVITY

Earl Ingerson, Chairman

Felix Chayes Patrick M. Hurley J. L. Kulp J. P. Marble

Your Committee to Consider the Formation of a Section of Geochemistry and Radioactivity met on November 6, 1950. Hurley could not be present, but the conclusions reached were outlined to him in a letter, and a letter from him, dated November 10, 1950, indicates that he is in complete accord with the report of the Committee.

The consensus at the meeting was that it would not be wise to attempt to establish a new Section at this time. The feeling was unanimous, however, that since papers on general geochemistry, petrology, and related subjects have been presented right along at meetings of the Section of Volcanology, it might be well to change the name of this Section so that its title would be more indicative of the interests of the members who are affiliated with it. This renamed Section might include both Volcanology and Radioactivity without having either subject mentioned in the name; it could thus do what those who proposed the new Section had hoped that it might do.

Several names were proposed. The Committee was not enthusiastic about any of them, but finally decided to recommend to the Executive Committee that it consider changing the name of the Section of Volcanology to the Section of Geochemistry and Petrology, and that this proposal be discussed at the annual meeting of the Section of Volcanology next spring and its recommendations secured before definite action is taken.

COMMITTEES OF THE UNION AND THE SECTIONS

List supplementary to the one published in the Transactions of October, 1950, part 2, pp. 111-114

STANDING COMMITTEES OF THE UNION

Membership: add Aaron C. Waters

Meetings: add Walter E. A. Ruska and Glenn E. Stout

SPECIAL COMMITTEES OF THE UNION

Resolutions: Mary C. Rabbitt (Chairman), Werner A. Baum, Francis G. Wells

COMMITTEES OF THE SECTIONS

Meteorology

Cloud Physics: Horace R. Byers (Chairman), Charles E. Anderson, George S. Benton, Roscoe R. Braham, Jr., Ferguson Hall, Helmut Weickmann

Atmospheric Diffusion: Glenn W. Brier (Chairman), E. Wendell Hewson, Heinz H. Lettau, Philip H. Lowry, Lester Machta

Problems of the Upper Atmosphere: W. W. Kellogg (Chairman), Michael Ference, Jr., Joseph Kaplan, A. G. McNish, Lyman Spitzer, Jr., J. A. Van Allen

Hydrology

Permanent Research Committees

(Note: Terms of appointment expire on June 30 of the year indicated.)

Chemistry of Natural Waters: add Otto M. Smith (1953)

Evaporation and Transpiration: add A. R. Croft (Chairman), H. F. Blaney (1953), Carl Rohwer (1953), J. M. Aikman (1953)

Glaciers: add P. D. Baird (1951), C. Max Bauer (1951), James L. Dyson (1951), Arthur Johnson (1952), Oliver Kehrlein (1952), Henri Bader (1953), Donald B. Lawrence (1953), Louis L. Ray (1953)

Ground Water: add C. O. Wisler (1952), William I. Gardner (1953), Nicholas A. Rose (1953)

Infiltration: add F. L. Duley (1952), Don Kirkham (1953)

Lakes: add Jack L. Hough (Chairman), L. C. Gottschalk (1951), James T. Wilson (1951), Albert L. Cochran (1952), S. T. Harding (1952), P. E. Church (1953), J. W. Johnson (1953), A. F. Spilhaus (1953)

Land Erosion: add E. A. Colman (1951), A. W. Zingg (1952), J. D. Sinclair (1953)

Physics of Soil Moisture: change C. M. Woodruff (1952) to (1953); add J. E. Christiansen (1953)

Precipitation: add W. E. Hiatt (1953)

SPECIAL ANNOUNCEMENTS

Thirty-Second Annual Meeting, Washington, D. C., April 30-May 2, 1951--Attention is called to the announcements in the October (p. 807) and the December (p. 954) issues of the Transactions regarding the Thirty-Second Annual Meeting to be held in Washington, D. C., April 30-May 2, 1951. Note that titles of papers, with three copies of the abstracts, are to be in not later than March 5, 1951, with advice concerning time required (ten to 20 minutes usually allowed) and projection equipment needed. Word may be sent to the office of AGU or the Section Secretary as shown in the October announcement. Programs may be closed in advance of that date if they are filled. See the December announcement with regard to rooms.

Ninth General Assembly of the International Union of Geodesy and Geophysics--This meeting is to be held in Brussels, Belgium, August 21-September 1, 1951. This is the last call for papers from sources in the USA, though the programs of some of the Associations may be closed by the end of February. If you plan to go, and desire to be a delegate or representative from the USA, please communicate word of this to the office of AGU without further delay. Make travel arrangements directly with your travel agent as soon as possible. Representatives attending from the USA will be supplied with information on accommodations, programs, and other matters as such material is received.

FRIEZ INSTRUMENT DIVISION
BENDIX AVIATION CORPORATION

Manufacturer of Meteorological Instruments

Taylor Avenue near Loch Raven Boulevard
Baltimore 4, Maryland

GEOPHYSICAL RESEARCH CORPORATION

Geophysical Prospecting
Application of Geophysical Methods in the Petroleum Industry

2607 North Boston Place
Tulsa 6, Oklahoma

INSTITUTE OF GEOPHYSICS

UNIVERSITY OF CALIFORNIA

Los Angeles 24, California

KEUFFEL AND ESSER COMPANY

Drafting, Reproduction, and Surveying Equipment and Materials
Slide Rules Measuring Tapes

300 Adams Street
Hoboken, New Jersey

RANNEY METHOD WATER SUPPLIES, INC.

Ground Water Exploration and Development

841 Alton Avenue
Columbus 3, Ohio

RUSKA INSTRUMENT CORPORATION

Developers, Designers, and Manufacturers of Instruments for Field and Observatory Use
Magnetic, Geodetic, Seismic, and Meteorological Work

4607 Montrose Boulevard
Houston 6, Texas

SEISMOGRAPH SERVICE CORPORATION

Seismic Exploration Service for
Oil and Gas Structures throughout the World

P. O. Box 1590
Kennedy Building
Tulsa 1, Oklahoma

SPRENGNETHER INSTRUMENT COMPANY

Manufacturer of Seismological and Geophysical Instruments
Instrumental Development and Research

4567 Swan Avenue
St. Louis 10, Missouri

TRANSACTIONS
AMERICAN GEOPHYSICAL UNION

Volume 32 APRIL 1951 Number 2

TIDAL VARIATIONS OF GRAVITY

M. S. Reford

Abstract--The changes in the value of gravity at Toronto with respect to time have been observed with a North American gravimeter. Readings were taken every quarter of an hour over a period of 29 days, partly by normal visual methods and partly by photographic recording. A drift curve for the instrument has been calculated and the residual fluctuations analyzed harmonically. The results yield the amplitudes and phases of the changes in gravity corresponding to the tidal constituents M_2, S_2, N_2, K_1, and O_1. The amplitudes of these constituents have been compared with the tide-generating potentials of the Sun and Moon to give the function of Love's numbers $m = 1 + h - 3k/2$. The analysis of the records for 29 days gives a mean value of m equal to 1.0(9) for the semidiurnal and 1.0(0) for the diurnal constituents. A separate analysis of the records for the first 15 days, which were taken by the more accurate visual method, gives m = 1.2(2) and 1.0(2) for the semidiurnal and diurnal constituents respectively. These results agree with those obtained by other methods of studying Earth tides.

Introduction--The modern gravimeter is an instrument which can readily be used for the study of Earth tides. As part of a program organized by the Shell Oil Co., a North American gravimeter was used at the University of Toronto to observe the tidal variations of gravity. Ordinary visual readings were taken from May 9-26, 1949, and the series was continued to June 9 by means of an automatic photographic recording apparatus. After the drift curve had been calculated, the residual variations were analyzed harmonically, and the results summarized as values of $1 + h - 3k/2$, a function of Love's numbers.

Observations and preparation of figures for analysis--The gravimeter was set up on a concrete block which had been laid in the ground of a basement time vault. The specifications of this block are: lat., 43° 39'7 N; long., 79° 23'7 W; height, 384.40 ft above M.S.L.; and g, 980.444 cm/sec^2.

Visual readings were taken by the usual method to the nearest 0.005 milligal two minutes before and two minutes after each quarter hour, the two readings being averaged to give a reading for the quarter hour. Figure 1 shows a typical gravity-time curve obtained in this way. The photographic recording apparatus consisted simply of a camera which took a photograph of the scale and hairline of the gravimeter at intervals of 15 min. The two methods of reading the instrument were basically different, for, in the first, the hairline was brought to the central scale mark and the dial reading noted, while, in the second, the deflections of the hairline from this mark were noted, the dial remaining still. The scale was calibrated after June 9, and the ratio of one scale division to one dial division was assumed to remain constant. It may be seen from Figure 2, which shows the change over from visual to photographic recording, that the photographs were less accurate than the visual readings. Mean readings, to the nearest 0.001 milligal, were calculated for each hour from three of the quarter-hour values.

The gravimeter mechanism was clamped only while the photographic recording apparatus was being set up. On both occasions when this was done, the reading rose with a sudden jump as may be seen from Figure 2. The amount of the discontinuity was estimated by trying to join the two parts of the gravity-time curve on either side of the jump. Two criteria were used: (1) The slope of the curve must be the same immediately on either side of the discontinuity. (2) The shape of the curve after the discontinuity has been removed must agree closely with the shapes of the corresponding curves on the day before and the day after the discontinuity occurred in the analysis.

Three assumptions were followed in allowing for these discontinuities. (1) The discontinuity died out in time. A linear decay is the simplest to consider and a decay time of 48 hr was assumed, because this appeared to give consistent results and was a convenient figure. Thus, if the reading rose suddenly by A at a certain time, A/2 must be subtracted from the reading 24 hr later while the readings 48 hr or more later are not altered. (2) The discontinuities did not die out in time. Thus A must be subtracted from all readings after the jump. (3) No readings are changed, that

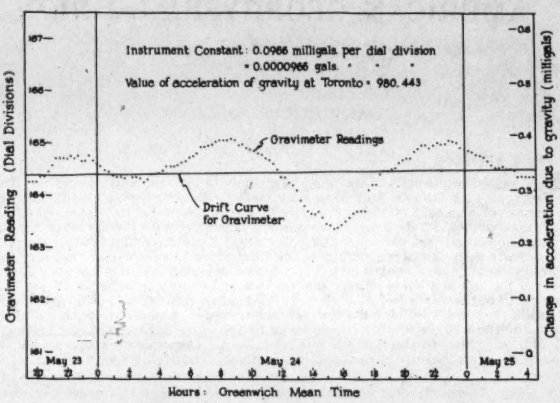

Instrument Constant: 0.0986 milligals per dial division
= 0.0000986 gals. " " "
Value of acceleration of gravity at Toronto = 980.443
Gravimeter Readings
Drift Curve for Gravimeter
Gravimeter Reading (Dial Divisions)
Change in acceleration due to gravity (milligals)
May 23
May 24
May 25
Hours: Greenwich Mean Time

Fig. 1--Gravity-time curve

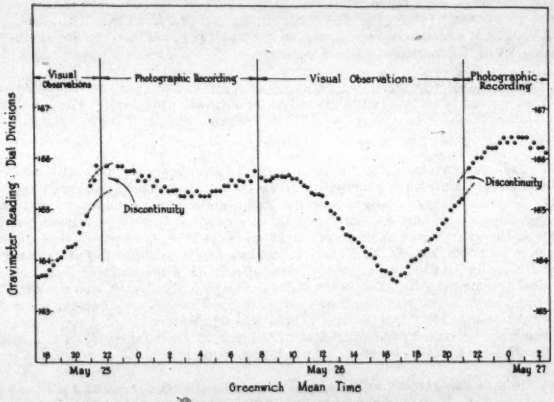


Fig. 2--Gravity-time curve during change-over from visual to photographic recording

is, the existence of a discontinuity is denied. This is very unlikely to be true, but was used to see what effect the ignoring of a discontinuity is likely to have. Finally, 12 missing mean hourly values were found by interpolating from the gravity-time curves.

Calculation of the drift curve--Now that a complete set of the values of gravity at every hour had been built up, the effect of the drift of the gravimeter had to be removed so that fluctuations about a constant value remained to be analyzed. The method followed was that given in the Admiralty Manual of Tides [DOODSON and WARBURG, 1941], section 13.8, for the calculation of mean sea level from observations of ocean tides. Assume that the gravimeter reading, y_t, at an hour t, equals the sum of a term for the drift, $\phi(t)$, and a series of harmonic functions, that is, let

$$y_t = \phi(t) + \sum_m (A_m \cos n_m t + B_m \sin n_m t) \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where n = the speed of a harmonic term in degrees per hour. Then

$$\left.\begin{array}{l} y_{t-19} + y_{t-14} + y_{t-9} + y_{t-4} + y_{t+1} \\ +y_{t-17} + y_{t-12} + y_{t-7} + y_{t-2} + y_{t+3} \\ +y_{t-11} + y_{t-6} + y_{t-1} + y_{t+4} + y_{t+9} \\ +y_{t-9} + y_{t-4} + y_{t+1} + y_{t+6} + y_{t+11} \\ +y_{t-3} + y_{t+2} + y_{t+7} + y_{t+12} + y_{t+17} \\ +y_{t-1} + y_{t+4} + y_{t+9} + y_{t+14} + y_{t+19} \end{array}\right\} = \sum_m 2 \cos n_m \, (\sin 12\, n_m / \sin 4\, n_m) \cdot (\sin 12.5\, n_m / \sin 2.5\, n_m) \cdot (A_m \cos n_m t + B_m \sin n_m t) + 30[\phi(t) + 0.130\, \phi''(t) + 0.007\, \phi^{iv}(t) + \ldots] \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

$$= \text{(say) } 30\, G(t)$$

where $\phi(t+m)$ has been expanded in a Taylor series with derivatives taken per 19 hr. The reason for using this particular combination of the y's is that the harmonic term on the right-hand side is zero, or very small, for all the more important tidal constituents. If this harmonic series and the terms involving derivatives of $\phi(t)$ are assumed to be negligible, $\phi(t)$, may be found, giving a point on the drift curve. A correction may be applied for the term $\phi''(t)$, if this is assumed to equal the second difference of the values of G(t) taken over 19-hr intervals, Δ^2, say.

Then $\phi(t) = G(t) - 0.13\, \Delta^2(t)$. This correction for the curvature of the drift curve will not be very accurate, but is unlikely to be of the wrong order. It was applied in the analysis to see whether its effect was appreciable..

In this manner, values of G were found at times four hours or less apart. These figures were then plotted as the drift curve, which is shown in Figure 3. Unfortunately, the readings did not cover 29 days + 38 hr, so that G could not be computed for the beginning and end of the series. However, the drift curve was extrapolated in two ways at each end, giving parts p, q, r, and s. It is hoped that the true drift curve should lie between p and q at one end, and between r and s at the other. These parts are so close together that they will not show up in Figure 3. The high rate of drift at the beginning of the observations was caused by the removal of the gravimeter cover to make an adjustment to the optical system.

In this way, 24 different drift curves were obtained. The resultant differences to be analyzed were distinguished by noting whether the drift curve followed p or q; I, II, or III; and r or s. Thus one set of results is denoted pIr.

Harmonic analysis--These sets of figures were analyzed harmonically by the method for the treatment of 29 days observations of ocean tides, given in the ADMIRALTY TIDE TABLES [1941]. For comparison, three more analyses were made covering the first, central, and last 15 days of

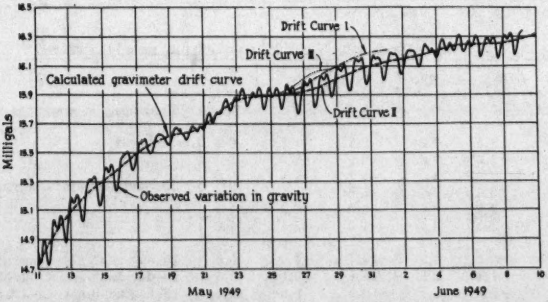


Fig. 3--Gravity-time curve and drift curves for whole period of observations

the set plr. In the analyses, the functions W and w were computed, and not taken from the schedules given in the Tide Tables.

DOODSON [1921, 1927] has given a very full expansion of the tide-generating potentials of the Sun and Moon as a series of harmonic terms with different amplitudes and arguments. From his tables it is a simple matter to extract the major constituents of the tidal variations of gravity on a rigid Earth. These will hereafter be called direct constituents. They are all spherical harmonics of the second degree. The phase lags of the observed constituents on the corresponding direct constituents are denoted by the Greek letter kappa.

The harmonic analyses yield the amplitudes and phases of the following tidal constituents: M_2, S_2, N_2, K_1, O_1, M_4, MS_4, and A_0. The suffices 1 and 2 show whether the constituent is diurnal or semidiurnal respectively. M_4 and MS_4 are quarter-diurnal constituents of importance in shallow-water tides. A_0 is a measure of the mean value of all the readings. These three terms were found to be negligible, as expected.

A summary of the results obtained is given in Tables 1 and 2. Each number from the 29-day analyses is the mean of the four sets involving p, q, r, and s. The ranges of variation of the amplitudes in these four sets are also given. The ranges of the phase lags do not exceed 0°.3, and are generally smaller. The direct constituents have been calculated from Doodson's tables.

It is, then, apparent that the correction for the curvature of the drift curve has a negligible effect; and furthermore, that so long as the discontinuities are recognized, and their magnitudes are correctly estimated, the length of time in which they decay has little effect. Even neglecting them altogether introduces a change of the order of only one per cent in the major terms.

The results of the 15-day analyses are not very consistent. N_2 particularly varies widely in

Table 1--Amplitudes of tidal constituents of gravity, given in thousandths of a milligal

Item	M_2		S_2		N_2		K_1		O_1		Remarks
	Amplitude	Range	Amplitude	Range	Amplitude	Range	Amplitude	Range	Amplitude	Range	
Direct	39.17	...	18.27	...	7.50	...	43.87	...	31.02	...	Tidal constituent on a rigid Earth
I	42.37	0.08	20.08	0.03	8.84	0.07	42.40	0.11	32.01	0.05	29-day analysis: Central day May 25
I[a]	42.42	0.05	20.06	0.06	8.84	0.07	42.35	0.07	32.03	0.04	
II	42.36	0.08	20.05	0.05	8.85	0.06	42.42	0.10	32.11	0.03	
II[a]	42.43	0.05	20.05	0.05	8.84	0.05	42.37	0.06	32.13	0.06	
III	42.83	0.04	20.59	0.05	8.03	0.06	43.04	0.12	32.04	0.03	
III[a]	42.92	0.09	20.67	0.06	8.01	0.06	42.78	0.05	32.07	0.01	
plr	46.80	...	23.08	...	12.39	...	40.67	...	35.30	...	15-day analysis: Central day May 18
plr	39.35	...	20.31	...	5.29	...	38.88	...	35.88	...	15-day analysis: Central day May 25
plr	43.14	...	17.32	...	4.05	...	41.74	...	28.92	...	15-day analysis: Central day June 1

[a]Correction for the curvature of the drift curve has been applied.

Table 2--Phase lags K of tidal constituents, given in degrees

Item	M_2	S_2	N_2	K_1	O_1	Remarks
Direct	0	0	0	0	0	Phase lag on a rigid Earth
I	2.5	7.8	-3.5	-1.8	0.8	29-day analysis: Central day May 25
I[a]	2.5	7.6	-3.6	-1.8	0.7	
II	2.5	8.0	-3.7	-1.8	0.9	
II[a]	2.4	7.7	-3.6	-1.8	0.8	
III	2.8	8.6	-5.0	-2.5	1.1	
III[a]	2.8	8.4	-4.9	-2.4	1.0	
plr	0.5	4.5	18.4	-4.9	-5.6	15-day analysis: Central day May 18
plr	4.5	1.8	25.1	-0.1	4.4	15-day analysis: Central day May 25
plr	-0.7	5.9	-19.2	1.5	-4.7	15-day analysis: Central day June 1

[a]Correction for the curvature of the drift curve has been applied.

amplitude and phase, and must, therefore, be ignored. The first 15-day period includes only a few hours of photographic recording, and the final 15 days includes one and a half days of visual recording. So if there is a marked difference between the results of the visual and photographic methods, this might be expected to show up in a comparison between the analyses for the first and last 15 days. Except for K_1, the amplitudes of the constituents of the last 15 days are smaller than those of the first. The phase lags show no systematic variation. This leads to no definite conclusion. However, since it is known that the accuracy of the photographic readings is less than that of the visual observations, it is worth considering the results from the first 15 days by themselves.

Interpretation of results as functions of Love's numbers.--All work on Earth tides may be summarized by simple functions of Love's numbers, which are defined below. The tide-generating potentials of the Sun and Moon can be expressed with sufficient accuracy by a series of spherical solid harmonics of the second degree. Suppose that such a potential is given by $A\rho^2 S$. Then the "equilibrium tide" in the ocean is given by AR^2S/g. Here A is a constant, ρ the distance from the center of the Earth, S a surface harmonic of the second degree, R the radius of the Earth, and g the undisturbed value of gravity. The equilibrium tide is the tide that would result on a rigid Earth if the particles in the ocean were to respond instantaneously to the tide-generating forces, with no effects arising from inertia, the presence of land masses, or the mutual gravitation of the particles.

Let the elevation of the solid surface be $h\,AR^2S/g$ above its mean position. Let the extra potential at external points due to the deformation of the Earth be $k\,AR^5S/\rho^3$, where h and k are Love's numbers. Their use is justified only if the solid Earth obeys an equilibrium tidal theory, which has been shown to be very nearly true. For fuller discussions of Love's numbers, see JEFFREYS [1929, Chap. 13] and LAMBERT [1931, Chap. 5 and 16].

So the total potential at points outside the Earth is given by

$$V = g\,R^2/\rho + A\rho^2 S + k\,AR^5S/\rho^3 \quad \ldots\ldots (3)$$

Now the value of gravity at the disturbed surface is

$$-(\partial V/\partial\rho)_{\rho=R+hAR^2S/g} = g\,(1 + hARS/g)^{-2} - 2\,ARS\,(1 + hARS/g) + 3k\,ARS\,(1 + h\,ARS/g)^{-4} \quad \ldots\ldots (4)$$

so the variable part of gravity is

$$g_1 = -(2h + 2 - 3k)ARS \quad \ldots\ldots (5)$$

neglecting second-order terms, since ARS is small. Then dividing the amplitude of an observed tidal constituent by the amplitude of the corresponding direct constituent gives

$$-g_1/2ARS = 1 + h - 3\,k/2 \quad \ldots\ldots (6)$$

So, taking the amplitudes as follows, the value of $1 + h - 3\,k/2$ may be found.

29-day analysis: Mean phase lag = 1°

	Amplitude	$1 + h - 3\,k/2$		
M_2	42.4	1.08		
S_2	20.1	1.10	Mean = 1.0(9)	
N_2	8.6	1.15		Mean = 1.0(4)
K_1	42.4	0.97		
O_1	32.1	1.03	Mean = 1.0(0)	

15-day analysis, central day May 18: Mean phase lag = -2°

	Amplitude	$1 + h - 3\,k/2$		
M_2	46.8	1.19		
S_2	23.1	1.26	Mean = 1.2(2)	
K_1	40.7	0.93		Mean = 1.1(0)
O_1	35.3	1.14	Mean = 1.0(2)	

The means given above are weighted in proportion to the amplitudes of the direct constituents.

The results for the semidiurnal and diurnal constituents should not necessarily be in close agreement. The ocean tides of these types do not bear an equilibrium ratio to each other, and the secondary effects of the oceans will produce changes in the tidal constituents of gravity. The diurnal temperature changes will also alter the constituents, particularly K_1 and O_1.

The corrections to be made for these secondary effects present a problem in all determinations of Love's numbers, and an accurate method of calculating them has yet to be devised. A method of estimating the effect of the oceans might be to set up a series of gravimeters on a line running from coast to coast of North America, in stable areas of the continent. These could perhaps be operated automatically with a recording apparatus for a period of a year. Such a program would not present insuperable practical difficulties, and would yield good determinations of $1 + h - 3k/2$ for the diurnal and semidiurnal constituents. The longer-period constituents could not be found, for they are included in the drift curve, and so are removed from the figures which are analyzed.

Applications of the results obtained--Determinations of Love's numbers are valuable in two ways. First, they give a measurement of the rigidity of the Earth as a whole. Second, they may prove useful in gravity surveys. The true drift of the gravimeter used here was small compared with the tidal variations of gravity. In gravity surveying these two variations are combined to form the drift curve, and frequent returns to a base station are necessary to find the drift. If the tidal variations of gravity were known, it would not be necessary to return to the base at such frequent intervals, for then only the true drift curve would have to be found. An investigation of this scheme would have to be made in the field, to see whether the higher, and perhaps discontinuous, rate of drift, induced by clamping and jolting the instrument, would render it impracticable.

The interpretation of Love's numbers into figures for the height of the Earth tides and the rigidity of the Earth involves a great deal of mathematical analysis and assumptions about the physical properties of the Earth. The work described above covers too short a period for the values of $1 + h - 3k/2$ to be considered very accurate, although they agree well with previous determinations of this and other functions of Love's numbers. Any such interpretations should cover all the work on Earth tides that has so far been done.

Acknowledgments--I am greatly indebted to all those who cooperated in taking these measurements of gravity, and regret that they are too many to mention by name. I also wish to thank E. C. Bullard and J. Tuzo Wilson for their assistance and advice.

References

ADMIRALTY TIDE TABLES, pt. III, Admiralty, 1941.

DOODSON, A. T., The harmonic development of the tide generating potential, Proc. R. Soc. London, v. A 100, pp. 305-329, 1921.

DOODSON, A. T., The analysis of tidal observations, Phil. Trans. R. Soc. London, v. A 227, pp. 223-279, 1927.

DOODSON, A. T., and H. D. WARBURG, Admiralty manual to tides, Admiralty, 1941.

JEFFREYS, H., The Earth, 2nd ed., Cambridge Univ. Press, 346 pp., 1929.

LAMBERT, W. D., The figure of the Earth, Nat. Research Coun. Bull., Washington, no. 78, 1931.

Additional citation

LAMBERT, W. D., Report on Earth tides 1939-1947, Bull. Géod., new series no. 14, Inter. Assn. Geod., Paris, pp. 383-401, December 1949.

614 Argyle Avenue,
Westmount,
Montreal 6, Canada

(Communicated manuscript received June 19, 1950; open for formal discussion until September 1, 1951.)

Transactions, American Geophysical Union Volume 32, Number 2 April 1951

SOME APPLICATIONS OF TENSOR ANALYSIS TO GEODESY

John A. O'Keefe

Abstract--The application of tensor analysis permits the determination of fundamental differences between coordinate systems without details of datum or corrections for higher-order terms. The notion of equipollence is discussed in its relation to grid azimuth, to convergence, and to the (t - T) correction. The notion of the covariant derivative is applied to the problem of the translation of a coordinate system, and certain corrections are derived.

There is a very close relation between the ideas and methods of geodesy and those of the branch of mathematics known as differential geometry; and especially between the theories of horizontal control and the section of differential geometry which deals with the intrinsic properties of surfaces. The close correspondence goes back to the invention of differential geometry by C. F. Gauss, who was the Director of Survey in Hannover. GAUSS [1880] wrote several mathematical papers dealing with the transformation of coordinates from one surface to another, in which the kernel of the idea is a notion derived from geodesy, and extended to the general theory of surfaces.

After Gauss's time, his ideas were developed by the geodesists and the mathematicians in divergent directions. Among the developments in the mathematical theory, two are of special interest to geodetic engineers, namely, the notion of equipollence, and the technique of tensor analysis.

The notion of equipollence is closely related to parallelism. True parallelism is, of course, impossible on the Earth's surface. Nevertheless, in geodesy we are accustomed to speak, often rather loosely, of a certain direction at a point A being parallel to another at B (see Fig. 1); or of the angle of convergence between, say, the meridian M through A and that through B. The fact that an angle of convergence can be specified means that there exists at B a direction D (not, in general, a meridian) having zero convergence with respect to the meridian through A; that is, in some sense, parallel to it. In this case, the statement that D is parallel to M means only that D and M make the same horizontal angle with the line of sight from A to B. It is clear that M and D will not have the same azimuth; that is, the idea of parallelism on the Earth's surface does not imply the idea of same azimuth.

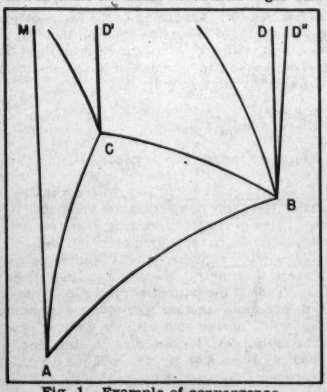


Fig. 1--Example of convergence and parallelism

In defining D as parallel to M, we had to make use of the geodetic line from A to B. If we had chosen a different line, we should have had to find a different direction at B parallel to M. For example, consider a new point C, and let D' be the direction at C parallel to M, as established by reference to the geodetic line AC. If we now transfer the direction D' to B along the line CB, we shall not get D, because if we did, the angles of the triangle ABC would add to 180°, whereas we know that they must add to 180° plus ϵ, where ϵ is the spherical excess. It follows that D as produced by the line AB and D" as produced from AC followed by CB must differ by the spherical excess. We see that we can only speak of D as being parallel to M along a certain line.

The definition of parallelism above is exactly that used in differential geometry up to the time of LEVI-CIVITA [1929], for a relation called parallelism in the surface.

The comparison can be pushed further. In lower-order surveys, we are accustomed to deal with a notion, superficially different, but actually closely related. This is the notion of plane azimuth, or calculated azimuth. It is especially used in connection with the simple traverses used for cadastral surveys and the like. On the first leg of the traverse, the surveyor sets up at a station A, levels his transit, and, if a meridian mark exists, sets his vernier to read zero, and clamps the upper plate. He now turns the telescope to the meridian mark, and clamps the lower plate, and unclamps the upper. He turns to the direction of B. His circle now reads the azimuth of B. He clamps the upper circle, and carries his transit to B. Here he sets up again, and plunges his telescope. He unclamps the lower circle, and turns to A. He then clamps the lower circle, and unclamps the upper. Now any direction on his circle will correspond to the plane azimuth carried from A.

The net effect of these operations is the same as if he had moved his circle from A to B by a pure shift, without any rotation in the horizontal plane. We note, however, that there has been a rotation around a horizontal axis, since the Earth is curved and the circle was leveled at both stations. The rotation is materialized by a slight shift of the telescope in the vertical plane. The plane azimuth defined by this operation can be carried forward again to a third station, and so on through the length of a traverse. Any two lines having the same plane azimuth will be regarded by the surveyor as parallel to one another.

LEVI-CIVITA [1929] defines what he calls equipollence, or parallelism, in the surface by means of a mathematical operation which is in all essentials the same as that of carrying azimuth. When applied to a succession of infinitesimal arcs, this operation permits us to define equipollence with reference to a line which is not a geodetic line, just as in the practical case it permits us to carry azimuth over a crooked course.

As before, we find that the direction of a line at B which is equipollent to one at A will depend on the course followed; and the difference for two courses will be equal to the spherical excess of the area enclosed, or, in the case of the Earth, one second for every 75 sq mi.

We began by saying that equipollence was not the same as equality of geodetic azimuths; and this is true if the path between the points A and B is any reasonable sort of path. But there is a path from A to B along which a line of, say, azimuth 90° at A is equipollent to a line of the same azimuth at B, if anyone were so perverse as to use it. This line starts from A, and goes along the meridian of A to the Equator. On this line, the azimuth carried by the surveyor remains the same as the geodetic azimuth, because the convergence is zero. Thence the surveyor proceeds along the Equator, where convergence is always zero, since sin ϕ is zero, to the meridian of B; and along this meridian he returns to B. Clearly, he will arrive at B with an azimuth equal to the geodetic azimuth.

Now let us close up the figure by a geodetic line from A to B. According to the ideas established above, the spherical excess of the quadrilateral so enclosed should be equal to the difference between the geodetic azimuth at B (which is equipollent to that at A via the Equator) and the plane azimuth carried to A directly via the geodesic. This is the convergence at A. Numerically, it is given by the area of the quadrilateral, taking the Earth's radius as unity.

$$A = \int_0^{\phi_m} \Delta\lambda \cos\phi \, d\phi = \Delta\lambda \sin\phi_m \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

From Figure 2, we can see that this area is the usual formula for the convergence.

We can study the notion of the (t - T) correction or second correction, in grid coordinates, in somewhat the same way. For example, on the transverse Mercator projection, we know that if a surveyor follows a line of constant northing, such as AC in Figure 3, starting with the correct grid azimuth (the so-called projected geodetic azimuth), he will require no corrections to his carried azimuth. The same is true along the central meridian. Thus if the path of survey goes from A to C, thence to D, thence along another line of constant northing from D to B, he will arrive at B with the correct projected geodetic azimuth. Now let him close up the loop by going along a geodesic from A to B. The spherical excess of this figure represents the sum of the angles θ_1 and θ_2. This gives us some insight into the usual formula for the (t - T) correction, which may be written, in radian measure.

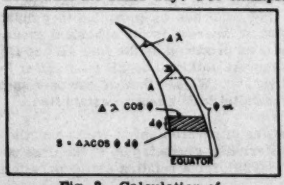


Fig. 2--Calculation of the convergence

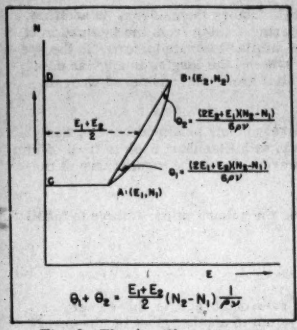


Fig. 3--The (t - T) correction

At A $(2E_1 + E_2)(N_2 - N_1)/6\rho\nu = (T_1 - t_1) = \theta_1$

At B $(2E_2 + E_1)(N_2 - N_1)/6\rho\nu = (t_2 - T_2) = \theta_2$

Sum $(1/2)(E_1 + E_2)(N_2 - N_1)/(\rho\nu)$

The sum is seen to be the area of ACDB expressed in units of $\rho\nu$, where $\sqrt{\rho\nu}$ is the radius of the osculating sphere. If E_1 and E_2 are nearly equal, this formula alone will permit the calculation of the (t - T) correction. Similar considerations can be applied to the Lambert projection.

We will now study the properties of a vector field. To fix our ideas, let us imagine that we have applied a displacement of some sort to a triangulation system. At each point, there will be a short vector, giving the displacement of the net in latitude and longitude or in easting and northing. We are interested in the variation of the vector from point to point, within a not very large scheme. We denote the components of the vector by x^1 and x^2, where the superscripts merely distinguish the one component from the other, and do not indicate powers. When we make a statement which applies to both x^1 and x^2, we write x^σ, for example. Now let us consider the variation of the displacement vector as we pass from station to station in the system. What properties do we consider desirable in the field?

It seems that if the displacement was called forth, as it often is, by the necessity of reconciling data along the boundary with another system, then what is most desirable is that the system be displaced without any rotation or stretch. If later circumstances arise which demand a rotation or a stretch, they can be handled separately. We thus confine ourselves to a displacement.

Provided that the area is not too large, we can define a pure displacement by saying that (1) the lengths of the displacement vectors are to be the same everywhere, and (2) the vectors are all to be parallel to one another. Now there is no trouble with the first requirement; this can be satisfied easily, if it is considered advisable. But the second requirement involves us in the ambiguity of the notion of parallelism. If, however, the net which is to be shifted is not too large, then the spherical excess of the area involved between any two plausible paths from one station to another will be small. A difference of a few seconds in the directions of the displacement vectors will be physically insignificant, since they are not likely to be more than a few hundred meters long.

Thus we are led to look for a way of defining a vector parallel to a given vector which is not very far away, and which will be approximately correct for any reasonable path. This is managed by the use of the covariant derivative. The inner workings of this complicated and powerful piece of mathematical machinery are given in mathematical texts on tensors [EISENHART, 1947; EDDINGTON, 1937; LEVI-CIVITA, 1929]. The notation here is that of Eisenhart. We shall confine ourselves to the applications. In application, the covariant derivative, evaluated at a point P, gives the rate of deviation of the vector from parallelism and from fixity of length as we pass from P in any direction into an area around P which is small enough so that terms involving the squares of the displacements can be neglected. In this small area, we can ignore the effects of spherical excess, so that it makes no difference which path is taken. In our problem, the covariant derivative measures, to the first order, the amount by which any proposed method of shifting a net fails to live up to our specifications. If we call the displacement vector A^μ and the coordinates x^σ, then the covariant derivative of A^μ with respect to x^σ is written

$$A^\mu{}_\sigma$$

and is given by

$$A^\mu{}_\sigma = \partial A^\mu/\partial x^\sigma + \left\{ \begin{matrix} \mu \\ \sigma\ \epsilon \end{matrix} \right\} A^\epsilon \qquad (2)$$

Here A^ϵ is a component of the same vector as A^μ. Both the case when it is the same component and that when it is not are involved in the equation. The curly brackets are known as the Christoffel three-index symbols of the second kind. They consist, in practice, of the first derivatives of the

scale factors of the coordinate system, multiplied by the scale factors themselves. In addition, if the coordinate system is not orthogonal, there are other terms arising from the inclination of the coordinate lines to one another, which are in many ways similar to scale factors. In the special case of latitude and longitude (which are an orthogonal system) the lengths in angular measure of one meter in the meridian and one meter in the parallel are to be considered as scale factors.

The calculation of the algebraic forms of the curly brackets in any practical case is a job which can be done by anyone who can make the calculus work, with Eisenhart open in front of him. I will not take space here to discuss it. It is important, however, to see the significance of the different members of (2).

First, consider the covariant derivative. This measures the amount of our failure to fulfill our plan; and accordingly it should be zero, so that

$$\partial A^{\mu}/\partial x^{\sigma} = -\left\{ \begin{matrix} \mu \\ \sigma\ \epsilon \end{matrix} \right\} A^{\epsilon} \qquad (3)$$

Next is the partial derivative. This term measures the rate of change in the numerical value of the displacement as we pass from one part of the system to another, that is, the change of the number of seconds of latitude or seconds of longitude of displacement. Clearly this is not the same thing as the actual change, because, for instance, one second of longitude is not the same at 38° N as at 39° N. Thus we shall expect to find that the partial derivative will not be zero; and, in fact, our aim is to discover exactly what it will be. To do this, we evaluate the right-hand side of (3). In so doing, it should be borne in mind that, by a usual convention with tensor analysts, the repetition of an index (such as ϵ) within a single term indicates that the index is to take in succession all the possible values (here only 1, 2) and then the results are to be added. Again, since both μ and σ can take the values 1 and 2, we shall expect to find that (3) is really four equations.

Let us see what (3) turns out to be for the case of latitudes and longitudes. If we make the superscript 1 correspond to latitude, ϕ, and the superscript 2 to longitude, λ (east), we have

$$\phi = x^1$$

$$\lambda = x^2$$

$$\Delta\phi = A^1 \text{ (the correction to } \phi)$$

$$\Delta\lambda = A^2 \text{ (the correction to } \lambda)$$

The Christoffel symbols turn out to be

$$\left.\begin{array}{ll} \left\{ \begin{matrix} 1 \\ 1\ 1 \end{matrix} \right\} = 3 \tan\phi\,(1 - \rho/\nu) & \left\{ \begin{matrix} 2 \\ 1\ 1 \end{matrix} \right\} = 0 \\ \left\{ \begin{matrix} 1 \\ 1\ 2 \end{matrix} \right\} = 0 & \left\{ \begin{matrix} 2 \\ 1\ 2 \end{matrix} \right\} = -(\rho/\nu)\tan\phi \\ \left\{ \begin{matrix} 1 \\ 2\ 1 \end{matrix} \right\} = 0 & \left\{ \begin{matrix} 2 \\ 2\ 1 \end{matrix} \right\} = -(\rho/\nu)\tan\phi \\ \left\{ \begin{matrix} 1 \\ 2\ 2 \end{matrix} \right\} = (\nu/\rho)\cos\phi\sin\phi & \left\{ \begin{matrix} 2 \\ 2\ 2 \end{matrix} \right\} = 0 \end{array}\right\} \qquad (4)$$

where, as usual, ρ is the radius of curvature in the meridian, and ν is the radius of curvature perpendicular to the meridian. From (2)

$$\partial(\Delta\phi)/\partial\phi = -3\tan\phi\,(1 - \rho/\nu)\,\Delta\phi \qquad (5a)$$

$$\partial(\Delta\phi)/\partial\lambda = -(\nu/\rho)\cos\phi\sin\phi\,\Delta\lambda \qquad (5b)$$

$$\partial(\Delta\lambda)/\partial\phi = (\rho/\nu)\tan\phi\,\Delta\lambda \qquad (5c)$$

$$\partial(\Delta\lambda)/\partial\lambda = (\rho/\nu)\tan\phi\,\Delta\phi \qquad (5d)$$

We can see the physical meaning of the different terms as follows: Eq. (5a) shows the apparent growth of the difference of latitude with increasing latitude. This is a small term (since ρ/ν is almost equal to unity) arising from the variation of the length of a degree of latitude. Eq. (5b) and (5c) correspond to an apparent rotation of the system. Remembering that $\rho\Delta\phi$ is a sort of northing (say, Δ_n) and is a differential of $\rho\phi$ (which we might call n), writing similarly Δe for $\nu \cos\phi\Delta\lambda$ and e for $\nu \cos\phi\lambda$, we have

$$\left.\begin{aligned} \partial(\Delta n)/\partial e &= -\Delta\lambda \sin\phi \\ \partial(\Delta e)/\partial n &= \Delta\lambda \sin\phi \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots (6)$$

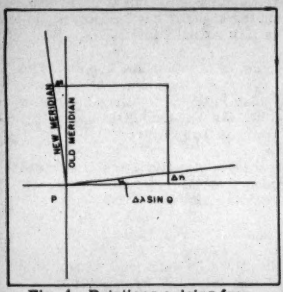


Fig. 4--Rotations arising from a shift of the graticule

If $\Delta\lambda$ is considered positive, this means that the graticule has been shifted westward over the terrain. Thus the new meridian through the central point is inclined to the old one as in Figure 4. It is seen that the value of e will be decreased north of P and increased south of it by this rotation. Similar considerations apply to the easting. The angle through which the apparent rotation has been made is $\Delta\lambda \sin\phi$. Remembering the Laplace equation

$$\alpha_A - \alpha_G = (\lambda_A - \lambda_G) \sin\phi \quad \ldots\ldots\ldots\ldots (7)$$

in which α is the azimuth, and the subscripts A refer to astronomic values, and G to geodetic values, it is clear that if this held before the shift, it will continue to hold afterward, since we shall change our geodetic azimuths by

$$\Delta\alpha = \Delta\lambda \sin\phi$$

This equation may also be viewed as the convergence on the arc of displacement.

Finally, (5d) shows the apparent growth of $\Delta\lambda$ with increasing latitude, an obvious consequence of the diminishing length of a second of longitude with increasing latitude.

If we distinguish the values which hold at the center-point from those at other points by the subscript o, we can write, for the total changes in ϕ and λ arising from displacements $\Delta\phi_o$ and $\Delta\lambda_o$ applied at the center-point

$$\Delta\phi = \Delta\phi_o - 3 \tan\phi_o (1 - \rho_o/\nu_o) \Delta\phi_o (\phi - \phi_o) - (\nu_o/\rho_o) \cos\phi_o \sin\phi_o \Delta\lambda_o (\lambda - \lambda_o) \ldots (8)$$

$$\Delta\lambda = \Delta\lambda_o + (\rho_o/\nu_o) \tan\phi_o \Delta\lambda_o (\phi - \phi_o) + (\rho_o/\nu_o) \tan\phi_o \Delta\phi_o (\lambda - \lambda_o) \ldots\ldots\ldots (9)$$

Let us now turn to the use of what are called rectangular coordinates. We note that all systems of rectangular coordinates which cover an area of more than, say, a city are based upon some map projection; that is, they can be imagined to be produced by ruling a square grid on a map on the given projection, and then transferring the squares to the ground. The distortions of the grid are thus the reciprocals of the map distortions.

Now among map projections, there are some which are suited only for the representation of the whole globe. Among these are, for example, van der Grinten's projection, and Eckert's projection. Leaving these aside, the others have one feature in common, namely, that at some point on the projection, and often along some line, the derivatives of the two scale-factors are all zero, and the coordinate system is orthogonal. This is true, for example, along the Equator on the Mercator projection; along the central meridian on the polyconic, Cassini-Soldner, and transverse Mercator; along the central parallel on the various conic projections, and around the center on the zenithal projections. This line is known as the axis of strength; and the competent cartographer sticks close to it in choosing his projection, especially if he hs setting up a rectangular coordinate system.

The Christoffel three-index symbols are composed of the derivatives of the scale-factors. Consequently, when these vanish, the Christoffel symbols vanish. It follows that within any grid coordinate system, and usually in the center, the Christoffel symbols will vanish. At such a point, we have, corresponding to (3)

$$\partial A^{\mu}/\partial x^{\sigma} = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (10)$$

It follows that, corresponding to (6), we have

$$\left.\begin{aligned}\Delta N &= \Delta N_0 \\ \Delta E &= \Delta E_0\end{aligned}\right\} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (11)$$

if N, E, are our rectangular coordinates, and ΔN_0 and ΔE_0 are the displacements at the origin. This approximation will be justified if the initial point is within the area, or not far from it, as is generally the case. It will then be as accurate as (8) and (9) in latitudes and longitudes.

We see that, regarded as a system of coordinates, the system of latitudes and longitudes has its axis of strength at the Equator; for if $\phi = 0$ the Christoffel symbols all vanish. The employment of latitudes and longitudes for calculations in middle or polar latitudes is attended with the same or greater difficulties (because of the sexagesimal units and the non-isometric character of the system) as the use of any other coordinate system far from its axis of strength.

In general, the use of tensors permits us to state in general terms the fundamental differences between possible coordinate systems, without confusions introduced by the differences in the historic origin of the systems, or by the differences in higher-order terms.

References

EDDINGTON, A. S., The mathematical theory of relativity, Univ. Press, Cambridge, 1937.
EISENHART, L. P., An introduction to differential geometry, Princeton Univ. Press, 1947.
LEVI-CIVITA, TULLIO, The absolute differential calculus (trans. by Miss M. Long), Blackie and Sons, Glasgow, 1929.
GAUSS, C. F., Werke, esp. Disquisitiones generales circa superficies curvas, Göttingen, v. 4, pp. 477-510, 1880.

Geodetic Division,
Army Map Service,
Washington 25, D. C.

(Manuscript received August 28, 1950; presented at the Thirty-First Annual Meeting, Washington, D.C., May 1, 1950; open for formal discussion until September 1, 1951.)

Transactions, American Geophysical Union Volume 32, Number 2 April 1951

HARMONIC ANALYSIS OF GRAVITY OBSERVATIONS

Albert J. Hoskinson

Abstract--Gravity-meter design has been improved in recent years so that it is now possible to measure accurately the small variations in gravity caused by the tidal forces. Some precise gravity surveys could no doubt be improved by applying corrections for the tidal effect and thus reducing all observations to a common datum.

More information is needed about the possible variations in the tidal forces from place to place on the Earth before tidal corrections can be applied with assurance to area surveys. A. Van Weelden of the Shell Oil Co. initiated a project in 1949 to measure the tidal variations at several stations throughout the world. The results from these observations are available for study by scientists interested in this subject. The harmonic analysis of some of the observations are also available and are presented.

Early in 1949 A. Van Weelden of the Shell Oil Co. initiated a project to measure the tidal variations of gravity at several stations scattered throughout the world. The initial plans provided for making simultaneous observations every 15 minutes for a period of 14 days at 25 stations. Frank Goldstone, Chief Geophysicist of the Shell Oil Co. in the United States, invited the U. S. Coast and Geodetic Survey to participate in the program. This invitation was accepted to the extent of providing the room and the observing force to make the observations at one station located in the gravity room of the building of the Department of Commerce in Washington, D. C. The gravity meter of the U. S. Coast and Geodetic Survey was at this time in use on a gravity survey in South America, and therefore not available for this test. A gravity meter for the project was furnished by LaCoste-Romberg Co. of Austin, Texas. This meter was thermostated at 42° C to provide a constant operating temperature. The meter had a reading accuracy of 0.01 milligal.

Frederick Romberg of the LaCoste-Romberg Co. came to Washington on May 2, 1949 and set up the instrument on the east pier of the gravity room. He checked and adjusted the instrument, and all of the observers were trained in the best method of observing with this instrument. This assured that all observations would be made in the same manner. Frederick Romberg also gave the observers a short course in trouble shooting for the electrical lighting and heating circuits in case of failure in either. A 24-hour test run was made before the actual observations started as a further check upon the method of observing and the proper functioning of the instrument.

The room where the observations were made is the standard base gravity station for the United States. The room was not thermostated for temperature control, but it is so well insulated that the temperature during the entire 15-day series varied only about one degree C. The temperature in this room may be easily controlled by using the ventilator and keeping the large overhead lights on or off as required. The observers watched the room temperature very closely during the entire series so that it was controlled very well. The gravity meter was therefore not subjected to any large temperature changes, and the drift remained very small and quite uniform throughout the entire series. The observing program was arranged for three shifts a day. Every two consecutive observers overlapped for four readings so that personal error, if any, could be determined.

The U. S. Coast and Geodetic Survey suggested soon after the project started that the series be extended to 15 days because that period was better for harmonic analysis than the 14-day series. This suggestion was adopted by the sponsors and practically all stations extended their series another day. We also volunteered to make the harmonic analysis for each station in North America and the one in Honolulu provided the necessary data were furnished.

Observations were made at the following places: Muna, Yucatan, Mexico; Honolulu, Hawaii; Panuco, Veracruz, Mexico; Houston, Texas (two meters); Beaumont, Texas; Austin, Texas; Pasadena, California; Albuquerque, New Mexico; Tulsa, Oklahoma; Washington, D. C.; Fort Morgan, Colorado; Salt Lake City, Utah; Toronto, Canada; Ottawa, Canada; and Edmonton, Canada (two meters). The results from each of these stations have been received, and the harmonic analyses have been made as shown in Table 1.

Table 1--Tidal harmonic constants from analysis of gravity observations

Place	North lat.	West long.	Length	Series begins	M_2[a]		S_2[b]		N_2[c]		K_1[d]		O_1[e]	
					H^f	κ^g	H^f	κ^g	H^f	κ^g	H^f	κ^g	H^f	κ^g
	° ′	° ′	day	1949	mgal	°	mgal	°	mgal	°	mgal	°	mgal	°
Muna, Yucatan, Mexico	20 28	89 43	14	May 9	0.0782	174.7	0.0394	190.9	(0.0152)	(166.0)	0.0508	179.1	0.0260	177.1
Honolulu, Hawaii	21 18	157 49	15	May 9	0.0806	191.2	0.0412	197.0	(0.0156)	(188.1)	0.0383	169.6	0.0326	179.2
Panuco, Veracruz, Mexico	22 10	98 10	14	May 11	0.0735	181.9	0.0350	193.9	(0.0143)	(175.5)	0.0410	177.6	0.0250	182.9
Houston, Texas Meter No. 10	29 42	95 26	15	May 9	0.0658	181.5	0.0308	172.4	(0.0128)	(186.4)	0.0334	183.8	0.0307	178.4
Houston, Texas Meter No. 20	29 42	95 26	15	May 9	0.0654	176.0	0.0306	171.3	(0.0127)	(178.5)	0.0453	175.5	0.0311	173.4
Beaumont, Texas	30 04	98 12	15	May 9	0.0660	179.4	0.0347	177.2	(0.0128)	(180.6)	0.0468	172.8	0.0338	180.3
Austin, Texas	30 17	97 44	14	May 7	0.0644	182.1	0.0286	186.3	(0.0125)	(179.8)	0.0439	181.1	0.0284	179.7
Pasadena, Calif.	34 09	118 10	29	May 17	0.0650	187.4	0.0310	185.1	0.0129	193.1	0.0559	183.8	0.0358	180.6
Albuquerque, New Mexico[h]	35 04	106 35	15	May 9	0.0535	187.9	0.0193	193.9	(0.0104)	(184.7)	0.0342	146.9	0.0330	209.3
Tulsa, Oklahoma	36 09	95 54	15	May 9	0.0605	182.9	0.0352	168.9	(0.0117)	(190.4)	0.0564	160.7	0.0328	176.9
Washington, D. C.	38 54	77 02	15	May 9	0.0567	177.7	0.0227	181.7	(0.0110)	(175.6)	0.0502	173.8	0.0356	180.8
Fort Morgan, Colorado	40 15	103 49	15	May 9	0.0515	183.9	0.0206	175.7	(0.0100)	(188.3)	0.0487	177.4	0.0359	174.9
Salt Lake City, Utah	40 46	111 51	14	May 10	0.0538	180.0	0.0216	188.9	(0.0104)	(175.2)	0.0601	188.4	0.0325	158.8
Toronto, Ontario	43 40	79 24	15	May 11	0.0458	183.2	0.0219	186.8	(0.0089)	(181.3)	0.0457	171.2	0.0347	178.4
Ottawa, Canada	45 44	75 43	14	May 9	0.0470	184.8	0.0243	185.2	(0.0091)	(184.6)	0.0512	182.6	0.0392	182.9
Edmonton, Canada Meter No. AG-1-29	53 33	113 29	15	May 9	0.0269	185.5	0.0170	173.6	(0.0052)	(191.9)	0.0475	179.7	0.0344	172.4
Edmonton, Canada Meter No. 40	53 33	113 29	15	May 9	0.0251	177.6	0.0182	184.7	(0.0049)	(173.8)	0.0446	172.9	0.0392	178.5

[a] M_2 = Principal lunar semidiurnal constituent.
[b] S_2 = Principal solar semidiurnal constituent.
[c] N_2 = Larger lunar elliptic semidiurnal constituent.
[d] K_1 = Lunisolar diurnal constituent.
[e] O_1 = Lunar diurnal constituent.
[f] H = Amplitude; values in parentheses are inferred.
[g] κ = Phase; values in parentheses are inferred.
[h] Readings at Albuquerque were made in units of 0.05 mgal which is about the same as the amplitude of the largest component. Values in parentheses are inferred.

It is expected that as the results are studied in detail we may: (1) increase our knowledge of the drift of gravimeters; (2) increase our knowledge of the rigidity of the Earth's crust; (3) determine the magnifying factor to be applied to the theoretical tidal effect on gravity for an ideal rigid unyielding Earth to allow for the elastic yielding of the actual Earth; (4) see what effect, if any, the local geological structure may have on the results; (5) see to what extent the results are affected by the ocean tides; and (6) determine whether additional observations and possibly a longer series of such observations are desirable at some future date.

Some preliminary studies have already been made of the results, and when the harmonic analyses of the remaining stations are available, more complete studies and conclusions may be made.

U. S. Coast and Geodetic Survey,
Washington 25, D. C.

(Manuscript received October 30, 1950; presented at the Thirty-First Annual Meeting, Washington, D. C., May 1, 1950; open for formal discussion until September 1, 1951.)

AIR-COUPLED FLEXURAL WAVES IN FLOATING ICE

Frank Press, A. P. Crary, Jack Oliver, and Samuel Katz

Abstract--Experimental studies of the propagation of elastic waves on floating ice sheets were made on the ice of Lake Superior and Lake Cayuga. Elastic waves were produced by small explosive charges detonated at various depths in the water, within the ice, and in the air. Seismic detectors consisting of a spread of geophones, a microphone, and a hydrophone recorded the resultant wave motion at varying distances.

Shots in the water produced the normal sequence of dispersive flexural waves. For shots in the air the dispersive flexural waves were absent and a train of constant frequency waves was observed, beginning gradually at the approximate time $t = r/2v_a$ and culminating with the arrival of the air wave at the time $t = r/v_a$ (r is the range and v_a is the speed of sound in air). These waves were interpreted as air-coupled flexural waves. The frequency of the air-induced waves is that of flexural waves whose phase velocity equals the speed of sound in air. The generated wave train precedes the air disturbance since the group velocity of flexural waves exceeds the phase velocity, all in accordance with classical theory. The frequency of the air-coupled vibration is simply related to the ice thickness.

The interpretation was supported by subsequent tests which consisted of shooting on shore and recording on the ice, shooting and recording on ice sheets of varying thickness, and recording air-coupled flexural vibrations with microphones.

Introduction--During a period of three weeks in February and March 1950, experimental studies of the propagation of elastic waves in floating ice sheets were made on Lake Superior and Lake Cayuga. These experiments were designed to study compressional, shear, flexural, and longitudinal surface waves in the ice-water system. In the course of the investigations an air-coupled flexural wave was identified. Sufficient time remained to firmly establish the existence of this wave by performing additional tests.

This paper presents the experimental data obtained for the air-coupled flexural wave and briefly reviews the theory. A detailed theoretical investigation is published in another paper [PRESS and EWING, 1950]. A paper dealing with air-coupled Rayleigh waves with application to ground roll is in preparation.

Experimental procedure--The standard method of seismic refraction measurements was employed. A spread consisting of eight vertical geophones and two horizontal geophones was placed on the ice surface. Additional data were occasionally obtained from a hydrophone at various depths in the water and a microphone in the air. Shots consisted of blasting caps or one-half pound TNT demolition blocks detonated at various depths in the water, in the ice, and at various heights in the air. The spread interval varied during the course of the experiments, and shot distances ranged up to 7414 ft. The instant of the explosion was transmitted to the recording truck by wire.

Two types of ice were encountered during the tests. Near shore a rough, hummocky ice sheet was found in which thickness variations of up to 50 per cent were not uncommon along a profile. About a mile off shore a smooth newly formed ice sheet was found. Ice thickness varied 15 per cent or less in the smooth sheet.

Flexural waves--Flexural vibrations in a floating ice sheet are essentially surface waves analogous to gravity waves on water, to Rayleigh waves on the surface of an elastic solid, or to flexural waves in a rod or thin plate. EWING and CRARY [1934] made a detailed investigation of these waves. They derived equations for phase and group velocity as a function of frequency, taking gravity, compressibility of water, and finite water depth into account. Their observations of dispersion of flexural waves on lake ice agreed quite well with the theoretically derived dispersion curves.

An expression for the phase velocity c of flexural waves is easily derived [EWING and CRARY, 1934] for the case of deep water (neglecting air)

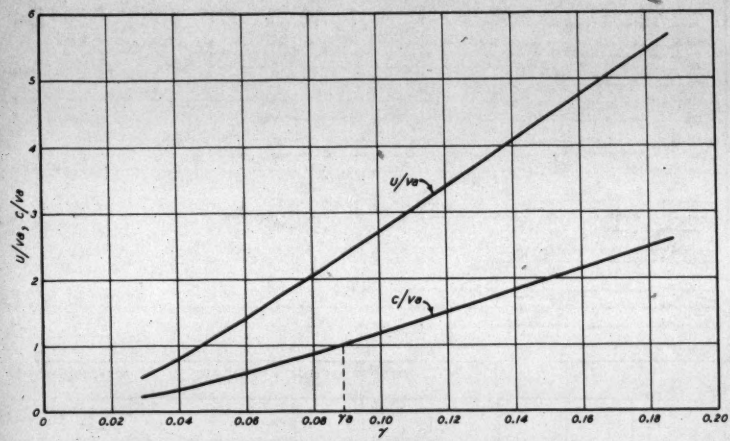


Fig. 1--Dimensionless phase and group velocity curves for flexural waves in a floating ice sheet

$$C^2 = [(1/3)\pi^2\gamma^2 V_p^2 + (\rho_w/\rho_i)\, g\lambda/4\pi^2\gamma]/[1 + (\rho_w/\rho_i)(1 - C^2/V_w^2)^{-1/2}(2\pi\gamma)^{-1}] \quad . . \quad (1)$$

where γ is the ratio of ice thickness H to wavelength λ, and is related to frequency f by the equation $\gamma = Hf/C$, v_p is the velocity of longitudinal waves in the ice sheet, v_w is the speed of sound in water, g is the gravitational constant, and ρ_w, ρ_i are the densities of water and ice respectively. It can be seen from (1) that for large wavelengths (γ small), the phase velocity is small, approaching the value $(g\lambda/2\pi)^{1/2}$ of gravity waves on deep water. As the wavelength decreases (γ increasing), the phase velocity increases. The gravity term in (1) can be neglected for wavelengths (or frequencies) for which $\gamma > 0.02$. Group velocity U can be computed as a function of γ from (1) and the familiar expression

$$U = C + \gamma dc/d\gamma \quad . . . . . \quad (2)$$

In Figure 1 dimensionless phase and group velocity curves computed from (1) and (2) are plotted against γ for the case v_p = 11,500 ft/sec, v_w = 4650 ft/sec, ρ_w/ρ_i = 1.0904. A typical record of flexural waves for a shot consisting of a cap exploded at the under surface of the ice at a spread distance of 4614 to 5014 ft is shown in Figure 2a. The ice thickness averaged 1.1 ft and the water depth 126 ft. The dispersion observed on the seismogram of Figure 2a is plotted as Figure 3. Good agreement with the theoretical group velocity curves for H = 1.0 to 1.1 ft is found. Records of flexural waves illustrated in Figure 2a were obtained for all shots located either in the ice or in the water. The amplitudes decreased as the depth of the shot increased, waves of higher frequency decreasing more rapidly than those of lower frequency, as one would expect from theory. Dispersion was found to be independent of distance provided shot distances were sufficiently large for the dispersion pattern to develop (>500 ft).

Air-coupled flexural waves--A pronounced change in record character was observed for shots fired on or above the ice surface. Figure 2b is the seismogram of a shot of one-half pound exploded in air 17 inches above the surface of the ice at the same location as the water shot illustrated in Figure 2a. Both records are aligned with respect to time after the shot instant. Flexural vibrations from the water shot are characterized by a long dispersive train beginning with waves of frequency 75 c/s and velocity about 2150 ft/sec and ending gradually with waves having a frequency of eight c/s and velocity about 650 ft/sec. The air shot consists almost entirely of a train of constant frequency vibrations the first waves of which travel with a velocity of about 2000 ft/sec. A

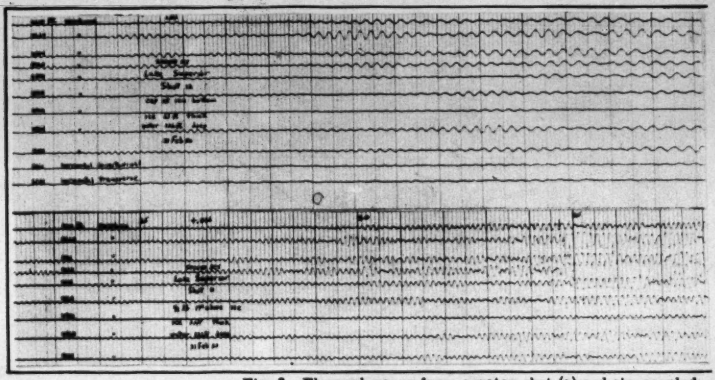


Fig. 2--Flexural waves from a water shot (a) and air-coupled

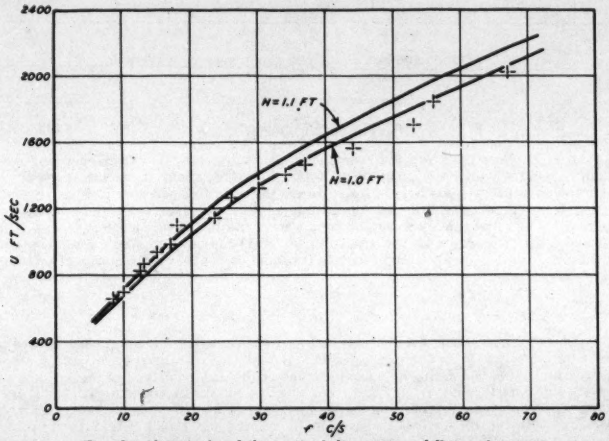
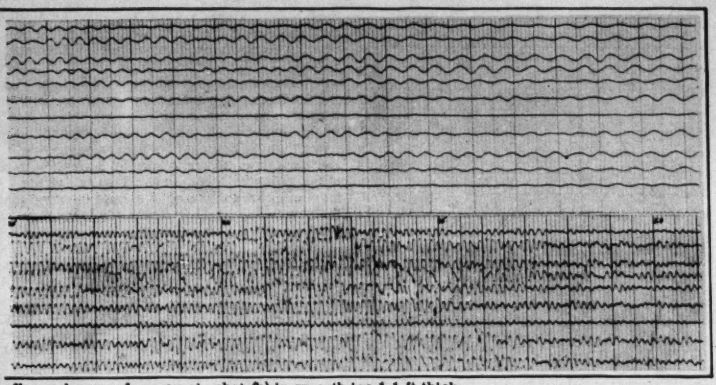


Fig. 3--Observed and theoretical dispersion of flexural waves

gradual increase of amplitude with time is observed (although some grouping tends to occur). The constant frequency waves build up until the arrival of a pulse (indicated by arrows), after which the amplitudes diminish rapidly.

Figure 4, a seismogram, recorded at reduced gain, of an air shot of one-half pound detonated one foot above the ice at a spread distance of 6114 to 6514 ft, clearly indicates the nature of this pulse. It consists of a single cycle wave traveling with the speed of sound in air. There is little activity in the air shot after the arrival of the air wave, whereas in the water shot, flexural vibrations continue to arrive after the time corresponding to the air wave.

Except for minor changes, the general characteristics of the records in Figure 2a were observed for all shots within the ice or in the water near the ice bottom. All air shots produced records similar to the seismogram of Figures 2b and 4.



flexural waves from an air shot (b) in smooth ice 1.1 ft thick

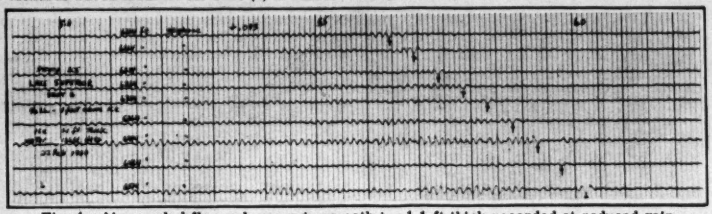


Fig. 4--Air-coupled flexural waves in smooth ice 1.1 ft thick recorded at reduced gain

The constant frequency train of waves culminating with the arrival of the air wave are interpreted as air-coupled flexural waves. A simple yet general explanation of the main characteristics of air-coupled surface waves can be given with the aid of the classical theory of traveling disturbances [LAMB, 1916ab]. If the reaction of the surface wave on the air is neglected, the air wave can be treated as a pressure pulse traveling over the surface of a dispersive medium with velocity v_a. We can think of the air wave as imparting a succession of impulses at infinitesimally small, equal intervals of time as it moves over the surface. Each impulse produces a dispersive train of waves. Superposition of the successive wave systems results in reinforcement only for those waves whose phase velocity is equal to the velocity v_a of the air pulse. The waves thus produced have a discrete frequency which can be obtained from the phase velocity curve of the dispersive medium from the value γ_a (see Fig. 1) corresponding to $c = v_a$. Since waves of a given frequency propagate with the group velocity associated with that frequency, the induced constant frequency surface wave will precede or follow the air wave according as $U > c$ or $U < c$. Group velocity exceeds phase velocity for flexural waves, and accordingly an air shot can be expected to produce a train of constant frequency waves ending abruptly with the air wave. Air-coupled hydrodynamic gravity waves in very deep water and surface elastic waves would follow the arrival of the air wave.

If the air-ice-water system is treated as a single acoustic unit, one can derive phase and group velocity curves analagous to those presented in Figure 1. N. Haskell (personal communication, March 10, 1950) derived such curves for the steady state. Identical curves were derived by PRESS and EWING [1950] in their subsequent investigation of the exact theory of air-coupled flexural waves originating in an impulsive point source. A striking feature of these curves (see Fig. 5) is the extreme steepness in the group velocity at γ_a. Since the predominant waves observed at a distant point are those whose frequency and velocity are determined by the group velocity curve [HAVELOCK, 1914], we can expect a train of waves of constant frequency $f_a = \gamma_a V_a / H$

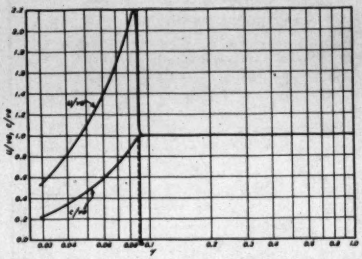


Fig. 5--Dimensionless phase and group velocity curves for air-coupled flexural waves

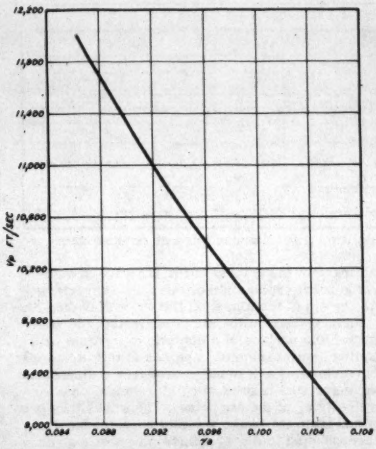


Fig. 6--Frequency parameter γ_a plotted as a function of longitudinal wave velocity

beginning at a time $t = r/2.2v_a$ and continuing until the time $t = r/v_a$. Calculation of the excitation function for these waves [PRESS and EWING, 1950] indicates that in an air shot they will predominate over waves whose travel time and frequency are determined from the remaining portions of the group velocity curve. For an ice or water shot the complete theory indicates that the constant frequency waves are vanishingly small and waves following the part of the group velocity curve to the left of the maximum predominate. It should be noted that the dispersion in these waves for frequency $f < f_a$ is almost identical with that obtained from the group velocity curve of Figure 1, which was calculated under the assumption that air had negligible effect of flexural waves. Thus it is only for an air shot that waves propagated according to the steep portion of the group velocity curve would be observed. It is these waves which we call air-coupled flexural waves.

The frequency of air-coupled flexural waves depends only on the parameter γ_a, the ice thickness, and the velocity of sound in air; γ_a depends on the elastic constants of the ice through (1). For smooth ice on Lake Superior $\gamma_a = 0.091$ and taking $v_a = 1070$ ft/sec, we can write the following simple equation for frequency in terms of ice thickness H (measured in feet)

$$f_a = 97/H \quad \ldots\ldots\ldots (3)$$

γ_a has been computed as a function of v_p, assuming the same constant values for the other parameters of (1) used earlier. The results of this calculation, plotted in Figure 6, can be used to obtain γ_a correct to within a few per cent.

On the smooth ice of Lake Superior the observed frequency f_a (see Fig. 2b and 3) averaged about 78 c/s. Ice thickness sampled at five locations along the profile gave an average value of 1.1 ft and the theoretically expected frequency calculated from (3) is 88 c/s, giving reasonably good agreement, in view of the uncertainty of the measured value of H.

Records obtained on Lake Cayuga gave a frequency of 150 c/s for the air-coupled flexural vibrations. Figure 7 illustrates a shot in which a cap was detonated at a depth of one inch in ice approximately eight inches thick. Water depth was 4.3 ft and a spread of 500 to 700 ft was used. Since $v_p = 10{,}200$ ft/sec on the Lake Cayuga ice, $\gamma_a = 0.097$ and we can write the following equation for frequency

$$f_a = 104/H \quad \ldots\ldots\ldots (4)$$

Since H = 0.66 ft, $f_a = 158$ c/s. Agreement with the observed value is good despite the fact that shallow water underlay the ice and (4) is based on deep water theory. The train of dispersive, long-period flexural waves which follows the air wave on the Lake Cayuga air-shot is probably due to the fact that the shot was partly in the ice, thus exciting both air-coupled waves and ordinary flexural waves.

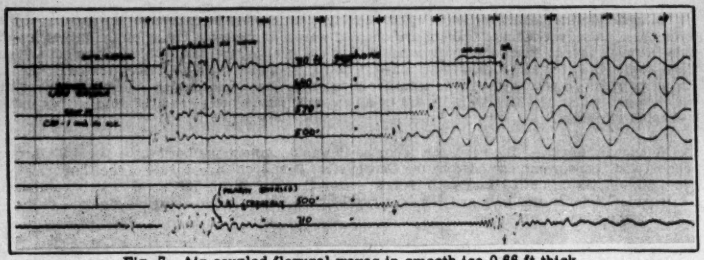


Fig. 7--Air-coupled flexural waves in smooth ice 0.66 ft thick

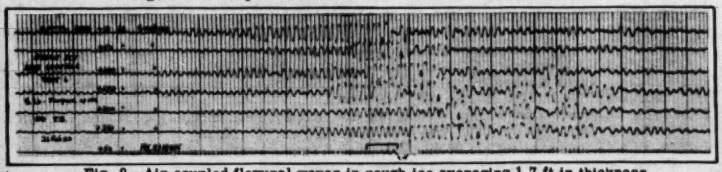


Fig. 8--Air-coupled flexural waves in rough ice averaging 1.7 ft in thickness

Records of flexural waves from both water and air shots were obtained for propagation paths across rough ice in which the ice thickness varied greatly. The flexural vibrations from a water shot in rough ice exhibited the characteristic dispersion although the waves were more irregular and amplitude variations were more pronounced. An air shot across rough ice produced the seismogram illustrated in Figure 8. In this shot, a one-half pound charge was detonated on the surface of the ice at an approximate distance of 4000 ft from the nearest geophone. A predominant frequency averaging 68 ± 3 c/s is observed for the air coupled waves. Since the elastic constants of rough ice are slightly different from those of rough ice the value of γ_a for the two media will differ. For longitudinal waves in rough ice we take the observed value $v_p = 10{,}000$ ft/sec. Using the same values for ρ_w, ρ_i, ρ_a, v_w, v_a as before, we find $\gamma_a = 0.099$. This gives for the rough ice

$$f_a = 106/H \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

Thickness of the rough ice measured at eight locations varied from 1.1 to 2.1 ft and averaged 1.7 ft. Computing the theoretical frequency from (5) gives 62 c/s, in good agreement with the observed value of 68 c/s.

Air-coupled flexural vibrations in rough ice show characteristics similar to those observed for shots in smooth ice. Wave amplitudes build up as the time for the arrival of the air wave is approached. However, the air wave does not arrive as a distinct pulse as is the usual case for smooth ice and some low frequency activity continues after the air wave. Only the microphone trace in Figure 8 registers the exact instant of the passage of the air pulse. Scattering, air-wave echoes, variations in group velocity, all due to irregularities in ice thickness, are believed to be responsible for these differences on the records obtained in rough ice. A striking feature of the seismogram in Figure 8 is the recording of a portion of the constant frequency wave train (indicated by a bracket) by a microphone located approximately one foot above the ice. Records have been obtained in which microphones have registered even larger portions of air-coupled vibrations. This is indeed confirmation of coupling between ice and air.

As an additional test, a one-half pound charge was detonated in a tree on shore at a distance of 20 ft from the edge of the ice sheet at a height of 20 ft above the ice surface. Unlike the usual air-shot records the seismogram obtained showed no longitudinal ice wave or compressional water wave. However, the air-coupled flexural waves were almost indistinguishable from those obtained for shot points over ice.

In several water shots for shot depths ranging from zero to 50 ft beneath the bottom of the ice a brief, faint, yet definite train of air-coupled waves is observed riding on the larger amplitude flexural waves. Since the shallow shots blow out, that is, the gas bubble breaks out and partially explodes in the air, a partial air wave is set up, inducing a coupled vibration. For the deeper shots which do not blow out it is tentatively suggested that some sound energy enters the air over the shot point by diffraction. Aided by a favorable air velocity gradient, this energy induces a coupled vibration.

Acknowledgments--The research reported in this document has been made possible through support and sponsorship extended by the Geophysical Research Directorate of the Cambridge Field Station, AMC, United States Air Force, under Contract W-28-099 ac-396. It is published for technical information only and does not represent recommendations or conclusions of the sponsoring agency.

References

EWING, MAURICE, and A. P. CRARY, Propagation of elastic waves in ice, Physics, v. 5, pp. 1-10, 1934.

HAVELOCK, T. H., The propagation of disturbances in dispersive media, Cambridge Tracts in Mathematical Physics No. 17, Cambridge University Press, 1914.

LAMB, H., On waves due to a traveling disturbance with an application to waves in superposed fluids, Phil. Mag. (6), v. 31, pp. 386-399, 1916a.

LAMB, H., On wave patterns due to a traveling disturbance, Phil. Mag. (6), v. 31, pp. 539-548, 1916b.

PRESS, FRANK, and MAURICE EWING, Air-coupled surface waves, Geophys. Res. Paper, Air Force Cambridge Research Laboratories, in press, 1950.

Lamont Geological Observatory, (F. P., J. O., S. K.)
Columbia University,
Palisades, New York
Air Force Cambridge Research Laboratories, (A. P. C.)
Cambridge 39, Massachusetts

Lamont Contribution No. 21

(Communicated manuscript received June 30, 1950, and, as revised, October 9, 1950; open for formal discussion until September 1, 1951.)

ELASTIC WAVE VELOCITIES IN SEDIMENTARY ROCKS

D. S. Hughes and H. J. Jones

Abstract--From a study of the transmission of dilatational pulses through rods it has been found possible to calculate not only the dilatational velocity but also the rotational (shear) velocity. From these velocities the elastic moduli of isotropic materials can be computed. The results are insensitive to boundary conditions and hence the method can be used when the material is surrounded by oil in a pressure chamber.

The velocities in sedimentary rocks have been measured in the ranges 0-1100 kg/cm^2 and 25-175 °C. In addition, one limestone and one dolomite have been measured up to 2000 kg/cm^2. The dilatational and rotational velocities and the elastic moduli as a function of pressure and temperature are presented for selected samples. A comparison of our results with those obtained by other methods is given. Although our measurements are based on pulses which have an equivalent frequency of 2.0-6.0 megacycles, there is no apparent discrepancy with low-frequency and static measurements. This would indicate that, at least for the rocks for which a comparison can be made, dispersion is not important. The elastic moduli are computed as functions of depth with an assumed gradient of 9.5 °C per 1000 ft. Values of Poisson's ratio are constant or increase slightly with pressure over the experimental range.

Introduction--It has been shown [MASON and McSKIMIN, 1947] that a plane dilatational pulse traveling parallel to the axis of a cylindrical rod is transformed into a series of pulses which travel with the velocity of dilatational waves in the material. The successive pulses are spaced at constant intervals in time by an amount that is proportional to the diameter of the rod and to the velocity of rotational waves in the material. Considering a very sharp pulse starting at time zero at the driver end of the rod, the arrival times at the detector end may be written [HUGHES, PONDROM, and MIMS, 1949]

$$t_{mn} = m\,L/V_D + Dn(V_D^2 - V_R^2)^{0.5}/V_D V_R \quad \ldots\ldots\ldots\ldots\ldots \quad (1)$$

where L = length of the rod, D = diameter of the rod, V_D = velocity of the dilatational (irrotational) waves, V_R = velocity of the rotational (shear, equivoluminal) waves, m = any odd integer 1, 3, 5, . . ., n = any integer 0, 1, 2, 3, . . ., and m and n are subject to the condition

$$m\,L > n\,D\,V_R/(V_D^2 - V_R^2)^{0.5} \quad \ldots\ldots\ldots\ldots\ldots \quad (2)$$

With this definition t_{10} is the arrival time of the direct pulse that has traveled the length of the rod with the velocity V_D; t_{11} is the arrival time of the second pulse which has been delayed by crossing the rod at the critical angle with the velocity V_R and traveling the remainder of the distance parallel to the axis with the velocity V_D; similarly, t_{12} has been twice delayed, t_{30} is the arrival time of the pulse reflected once from the detector end and once from the driver end, etc. With metal rods of good transmission characteristics, as many as 30 successive pulses corresponding to m = 1, 3, 5, . . . 17 and n = 0, 1, . . . 7 can be identified. In rocks the transmission is poor and, in general, only arrivals t_{10} and t_{11} can be read accurately although t_{12}, t_{13}, and t_{30} can be identified occasionally at the higher pressures.

Apparatus and procedure--The basic instrument of the electronic apparatus is the TS-100/AP circular sweep oscilloscope (see Fig. 1) [HUGHES, PONDROM, and MIMS, 1949; HUGHES, BLANKENSHIP, and MIMS, 1950]. This instrument has a free-running 80.86 kc circular sweep. Each revolution is, therefore, 12.368 μ sec in duration. An internal trigger generator is accurately synchronized at a sub-multiple of 80.86 kc, usually about 200 trigger pulses per second. These pulses are very accurately synchronized to fire at the instant the circular sweep passes through zero on the screen. The trigger pulses pass internally to a delay multivibrator. The delay of this multivibrator may be varied from about five to 800 μ sec. At the end of the delay period the circular sweep is turned on for one revolution. Thus, any event impressed on the radial electrode of the tube may be timed very accurately by counting the revolutions that appear after the trigger pulse. Externally, the trigger pulse is transmitted through the delay line which delays it

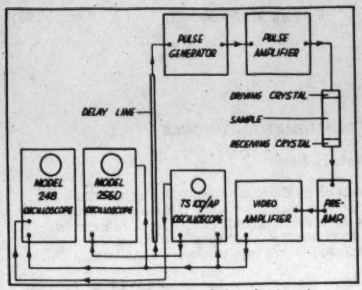


Fig. 1--Block diagram of the electronic apparatus

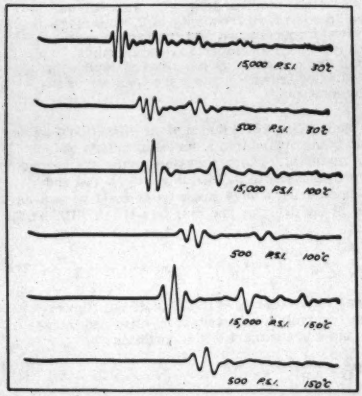


Fig. 2--Arrivals in jacketed quartz monzonite

about 3.5 μ sec and then to the pulse generator. The pulse generator provides an output pulse accurately synchronized with the trigger. The output pulse has a rise time of about 0.3 μ sec. Its duration may be varied from about 0.6 μ sec to 60 μ sec and its amplitude from about 20 to 180 volts. With metals, these pulses are sufficient, but to provide energy for rocks and similar materials a pulse amplifier follows the pulse generator. This amplifier uses a 6AG7 tube to sharpen and invert the pulse, an 807 tube as an amplifier, and a second 807 as a cathode follower for an output tube. This amplifier provides pulses with a rise time of 0.2 μ sec and about 800 volts amplitude.

These pulses are impressed on the driving quartz crystal and generate a very sharp elastic wave in the sample. The waves are received at the opposite end of the sample by a similar crystal. The output of the receiving crystal goes through the pre-amplifier and main amplifier to the oscilloscopes. The received signal is sent to the radial electrode of the TS-100 AP as all precise times are read on this instrument. The distortion inherent in the circular sweep, however, makes it desirable to check the wave form with the linear display on the 248 oscilloscope which is equipped with fixed sweeps of 5, 25, 100, and 1000 μ sec duration. By utilizing the delay gate of the TS-100 AP, any of the above sections of the received signal after the trigger may be displayed on the screen and photographed. Thus, for example, the portion of the signal received during the period 25 to 50 μ sec after the initial pulse may be displayed on the screen and examined in detail or photographed.

The validity of (1) has been checked by observations on a variety of materials. The most thorough checks have been carried out on brass and steel. These have consisted in showing that the interval between t_{1n} and t_{1n+1} is accurately proportional to the rod diameter and is independent of rod length. The diameters were varied from 0.25 to 2 inches and the lengths from two to 48 inches. This relation is also verified by the fact that V_D and V_R computed from the observations and the elastic constants are apparently accurate to about two parts in one thousand.

With rock samples, only t_{10} and t_{11} can be read dependably and at low pressures and high temperatures (100-150 °C) t_{11} sometimes becomes unreadable. For most samples, t_{10} is of the order of 12.00 μ sec and for $p > 500$ lb/in^2 it can always be read to ± 0.05 μ sec and usually to ± 0.03 μ sec. This gives a probable error of three to five parts per thousand in V_D. Usually t_{11} is of the order of 20 μ sec and can be read to ± 0.05 μ sec; the equivalent error in V_R is about one part per hundred.

Figure 2 shows the arrivals in quartz monzonite for various pressures and temperatures. The "improvement" in transmission with increasing pressure and decreasing temperature is clearly shown. This sample was enclosed in a copper-foil jacket. Early workers [ADAMS and WILLIAMSON, 1923] had realized the importance of enclosing samples in impervious jackets so that the properties of the aggregate might be investigated. In the present work [HUGHES and JONES, 1950], the effect of excluding or admitting the oil to the rock has been investigated. The chief effect of the oil penetrating the rocks is a considerable increase in velocity at low pressures; at higher pressures the difference becomes much smaller and in some cases the jacketed sample may show a higher velocity than the open sample.

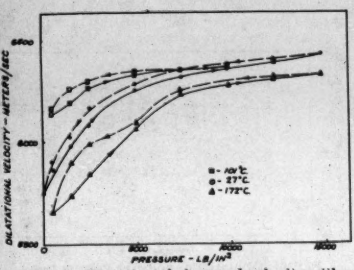


Fig. 3--Variation of observed velocity with pressure for dolomite No. 86

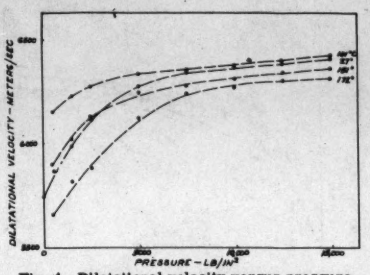


Fig. 4--Dilatational velocity versus pressure for dolomite No. 86

For the most part measurements have been confined to the range 0-1100 kg/cm^2 in pressure and 25-175 °C. The apparatus is being continually modified and recently the pressure range has been extended to 2500 kg/cm^2. Some results have been obtained in this range. It is expected to increase the upper pressure limit to 6000 kg/cm^2 and the temperature limit to 300 °C in the near future.

Description of materials--A group of 11 sedimentary rock samples was studied. This group, furnished by the Shell Oil Co., was selected from cores derived from two wells in West Texas. Single specimens of limestone, shale, sandstone, and several dolomites were investigated. The following brief descriptive material on samples specifically referred to in this paper is based upon the study of thin sections and core-log reports:

No. 22--Dolomite, subsurface depth 8270 ft, Ellenburger (Ordovician). A brown, medium crystalline glauconitic dolomite with thin shale partings. The density is 2.720 gm/cc.

No. 24--Sandstone, subsurface depth 8350 ft, Wilberns (Cambrian). A white, medium to coarse-grained, poorly sorted sandstone with accessory glauconite, pyrite, and calcareous material. The density is 2.529 gm/cc. The measured porosity is 4.8 per cent.

No. 85--Shale, subsurface depth 7205 ft, Atoka (Pennsylvanian). A black, calcareous shale rich in organic material. The density is 2.75 gm/cc.

No. 86--Dolomite, subsurface depth 7670 ft, Ellenburger (Ordovician). A buff, fine to medium crystalline dolomite with abundant bentonitic and shaly inclusions. The density is 2.79 gm/cc.

No. 88--Limestone, subsurface depth 7303 ft, Des Moines (Pennsylvanian). A gray, microcrystalline, carbonaceous limestone with high porosity. The density is 2.653 gm/cc.

No. 89--Dolomite, subsurface depth 7360 ft, Ellenburger (Ordovician). A buff, medium crystalline, cherty dolomite with shale streaks and many calcite-filled fractures. The density is 2.789 gm/cc.

No. 90--Dolomite, subsurface depth 7575 ft, Ellenburger (Ordovician). A brown, very finely crystalline dolomite with fractures that are partially filled with shale. The density is 2.796 gm/cc.

Discussion of results--Figure 3 shows the observed velocity variation with pressure for dolomite No. 86. It gives the first data taken with this sample and demonstrates two effects that have been observed in practically all rocks, both igneous and sedimentary. The velocities measured with decreasing pressures are higher than those measured with increasing pressures. Usually the velocity at the end of the cycle is the same as at the beginning. This sample shows a permanent increase. After a "run" at elevated temperatures, the room-temperature velocity is usually higher. A second heating cycle to the same temperature usually results in only a minor increase, but heating to a higher temperature will again increase the room-temperature velocity. This effect can reasonably be ascribed to compaction of the sample.

Apparently a rock can be stabilized for a certain pressure and temperature range (see Fig. 4). Extension of the range should, then, cause renewed improvement of the rock, as confirmed by measurements on limestone at 35,000 lb/in^2 and 175 °C (see Fig. 5). The improvement effect is slight for igneous rocks, usually less than one to two per cent. For sedimentary rocks the increase in velocities is two per cent or less at pressures above 5000 lb/in^2. At the low pressures it may be as much as ten per cent. In all cases, the percentage change in V_R is less than that in V_D.

The improvement effect shows the importance of past treatment upon the present elastic

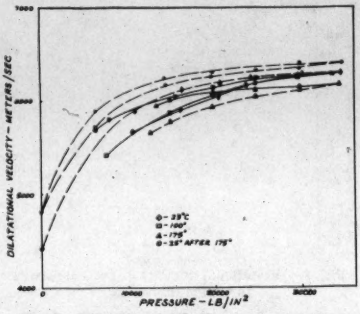


Fig. 5--Dilatational velocity versus pressure for limestone No. 88

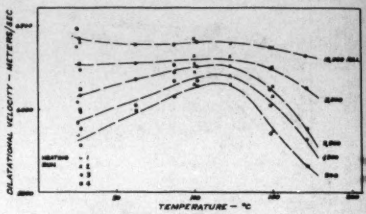


Fig. 6--Dilatational velocity versus temperature for dolomite No. 86

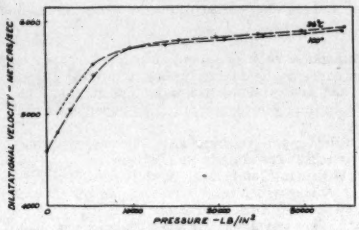


Fig. 7--Dilatational velocity versus pressure for sandstone No. 24, enclosed

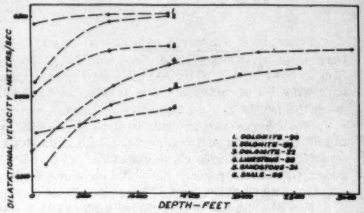


Fig. 8--Dilatational velocity versus depth for sedimentary rocks, enclosed

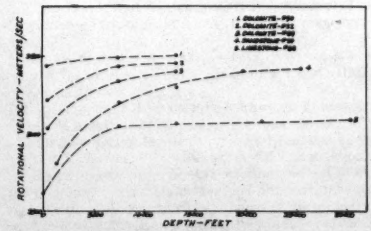


Fig. 9--Rotational velocity versus depth for sedimentary rocks, enclosed

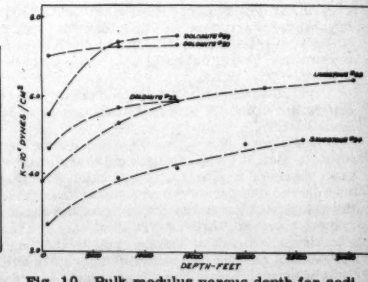


Fig. 10--Bulk modulus versus depth for sedimentary rocks, enclosed; assumed gradient 9.5 °C for 1000 ft

properties of rocks. Both the geological history and the laboratory handling influence the wave velocities and elastic properties. In the present work, rough treatment of samples during preparation and testing was probably negligible. The effect of varying pressure-temperature environment in a rock's geological past remains, however, an unsolved enigma.

Table 1--Poisson's ratio for sedimentary rocks, enclosed samples

Rock	Poisson's ratio				
	Approximate depth, feet				
	400	7,800	13,100	21,000	30,500
Dolomite No. 22	0.249	0.265	0.268	....	....
Dolomite No. 89	0.299	0.310	0.314	....	....
Dolomite No. 90	0.298	0.300	0.299	....	....
Limestone No. 88	0.290	0.295	0.317	0.323	0.329
Sandstone No. 24	....	0.229	0.229	0.252	....

Table 2--Well data, and velocities V_D in ft/sec

Rock	Description	Well	Depth	Formation	V_D	
					Experimental[a]	Seismic
			ft		ft/sec	ft/sec
85	Shale (carbonaceous, calcareous)	H	7205	Atoka +13	17,400	12,910
89	Dolomite (cherty, calcareous, shaly)	T	7360	Ellenburger -11	20,900	22,700
28	Dolomite fractured (shaly)	H	7230	Ellenburger -12	17,500	22,700
87	Dolomite (carbonaceous, calcareous)	H	7265	Ellenburger 47	19,700	22,700
90	Dolomite (crystalline)	T	7574	Ellenburger 225	21,400	22,700
86	Dolomite calcite (bentonitic, shaly)	T	7670	Ellenburger 321	20,800	22,700
91	Dolomite fractured (shaly)	T	8232	Ellenburger 883	22,200	N.S.[b]
22	Dolomite (glauconitic, shaly)	T	8270	Ellenburger 921	19,600	N.S.
24	Sandstone (glauconitic)	T	8350	Wilberns	17,600	N.S.

[a]At 100° C, 7500 lb/in^2. [b]N.S. means no seismic data.

In previous work on igneous rocks an increase in temperature always caused a decrease in wave velocities. Several of the dolomites show an increase in wave velocities with temperatures up to 100-125 °C. Further increase in temperature causes a decrease (see Fig. 6).

Figures 5 and 7 show the variation in V_D with pressure and temperature for samples 88 and 24 at pressures up to 35,000 lb/in^2. Figure 7 shows that with sandstone the pore space has been closed up at 10,000 lb/in^2.

The variation of velocities and elastic moduli with depth has been computed from the data assuming a temperature gradient of 9.5 °C per 1000 feet of depth. Figures 8, 9, and 10 show the calculated variation in V_D, V_R, and k, the bulk modulus, with depth. Table 1 shows the variation of σ, Poisson's ratio, with depth. The probable error in these values of σ is about $\pm$0.005. Except for the dolomite No. 90, all samples show a definite increase in σ with depth.

Vertical-well velocity surveys for the two wells from which samples came were made available by the Shell Oil Co. Table 2 presents a comparison of laboratory and seismic values of V_D. Except where laboratory samples are near boundaries of seismic velocity intervals, agreement is rather good. The laboratory values seem to be consistently lower, suggesting a possible dispersion effect. The seismic velocities, however, are subject to errors of at least ten per cent. Furthermore, comparison with a horizontal seismic velocity survey shows agreement within one to two per cent (personal communication from F. A. Van Melle of the Shell Oil Co., Houston, Texas).

The work of Ide, of BIRCH and BANCROFT [1938], and of others had indicated negligible dispersion for rocks at frequencies up to several hundred kilocycles. Present results on igneous and sedimentary rocks confirm and extend this, at least up to five megacycles.

At pressures above 15,000 lb/in^2 the rate of change of velocity is rather small as indicated by our scanty measurements to 35,000 lb/in^2. At present and in the geologic past, sediments accumulated in geosynclines to depths of at most 30,000-50,000 ft. At these depths the pressure and temperature are about 35,000 lb/in^2 and 300-350 °C respectively. Thus modification of the present apparatus to attain these values should make possible the gathering of significant data.

Acknowledgments--This paper includes part of the thesis offered toward the degree of Ph.D.

in Geology by H. J. Jones, Humble Oil and Refining Company Fellow in Geology. The work was supported by the Office of Naval Research under Contract N6onr-266, T. O. VIII, and by research grants from the Shell Oil Co.

References

ADAMS, L. H., and E. D. WILLIAMSON, On the compressibility of minerals and rocks at high pressures, J. Franklin Inst., v. 195, pp. 475-529, 1923.

BIRCH, F., and D. BANCROFT, The rigidity of rocks, pt. 2, J. Geol., v. 46, pp. 128-132, 1938.

HUGHES, D. S., E. B. BLANKENSHIP, and R. L. MIMS, Variation of the elastic moduli and wave velocities with pressure and temperature in plastics, J. Appl. Phys., v. 21, pp. 294-297, 1950.

HUGHES, D. S., and H. J. JONES, Variation of elastic moduli of igneous rocks with pressure and temperature, Bull. Geol. Soc. Amer., v. 61, pp. 843-856, 1950.

HUGHES, D. S., W. L. PONDROM, and R. L. MIMS, Transmission of elastic pulses in metal rods, Phys. Rev., v. 75, pp. 1552-1556, 1949.

MASON, W. P., and H. J. McSKIMIN, Attenuation and scattering of high frequency sound waves in metals and glasses, J. Acoustical Soc. Amer., v. 19, pp. 464-473, 1947.

Department of Physics,
The University of Texas,
Austin, Texas

(Manuscript received July 21, 1950; presented at the Thirty-First Annual Meeting, Washington, D. C., May 3, 1950; open for formal discussion until September 1, 1951.)

Transactions, American Geophysical Union Volume 32, Number 2 April 1951

A COMPARISON OF ICING CONDITIONS ON MOUNT WASHINGTON WITH THOSE ENCOUNTERED IN FLIGHT

Wallace E. Howell

Abstract--Icing clouds at Mount Washington have a slightly smaller mean drop size, a narrower drop-size spectrum, a slightly lower temperature, and quite comparable liquid water content when compared with those in the free air. The ranges of occurrence of these properties on the mountain and in the free air overlap broadly, differing markedly only at their extremes. Despite orographic effects, non-local influences principally determine cloud constitution on the mountain. Cloud data from mountain stations have application to theoretical, forecasting, and climatic studies.

Ice accretion in flight can be duplicated in natural wind at Mount Washington by a sliding scale reduction to approximately one fifth scale, except for characteristics directly involving the speed of drop impact. Form and density of ice on small objects overlap broadly those observed in flight. Mountain stations have some practical advantages of economy and freedom from space, weight, and safety limitations, and may be used, among other things, for instrument development and study of ice distribution on complex shapes.

Introduction

Despite the recurrent predictions that aviation's dependence on weather will end with the introduction of each new aid to air navigation, the end of the demand for research and engineering investigations of the icing hazard on aircraft is not yet in sight. A mountain whose top is frequently in icing clouds with strong natural winds offers certain advantages for these investigations. Among these are: there is no limit to the bulk and weight of equipment that can be used with the icing tests; the hazards of flight through icing conditions are eliminated; personnel can live and work at ease; reference materials, tools, and supplies are available during the tests; and the expense per hour of icing time is much lower than for icing investigations carried on in flight.

Although these advantages have been increasingly utilized in icing researches at Mount Washington during the past 15 yr, there have been doubts in the minds of some investigators regarding the degree to which icing at Mount Washington is representative of conditions in the free air. It is the purpose of the paper to consider this question in some detail.

There are three aspects to the question: (1) the icing cloud itself, its characteristics of drop size, liquid water content, and drop-size distribution, and their representativeness of free-air conditions; (2) the physical processes by which the icing cloud becomes ice on an aircraft; the differences that there may be in the dynamics of ice deposition between mountain and flight conditions; and (3) the differences in the form and density of the accumulated ice.

The icing cloud

Icing of aircraft results when droplets of supercooled water in a cloud strike the surface of an airplane and freeze there. The meteorological characteristics of the cloud that relate to icing are the temperature, the liquid water content, and the proportion of liquid water contained in drops in each portion of the range of drop sizes. The latter is usually described in terms of the mean effective drop size, which is the drop size that would give the same water interception from a cloud of uniform drops, other things being equal, and a measure of the breadth of distribution of drop sizes. The mean effective drop size differs only trivially in nearly all cases from the volume median drop size, and the two are used interchangeably.

The drop-size distributions vary individually, but in the mean they assume very nearly the shape of a normal Gaussian distribution of the volume with drop size and many of the individual distributions also fit the Gaussian quite closely. For a single measure to express the breadth of the distribution, the standard deviation of the drop diameters of the volume distribution from the volume median diameter $\bar{d}$ is therefore suitable. For the purposes of cloud physics it is often more

convenient to use a modulus of distribution m defined as

$$m = \sqrt{2}\ \sigma/\bar{d}$$

The majority of the measurements that have so far been made of the liquid water content, drop size, and drop-size distribution both in flight and at Mount Washington, have been made with the multicylinder icing meter. This instrument, as generally used, gives values of liquid water content and drop size with a probable error of the order of ten per cent of the observed values. It gives only an approximate value of the drop-size distribution modulus, with a probable error varying from about 0.5 units of modulus under the conditions of use at Mount Washington to a value probably greater than 1.0 in flight.

Liquid water content--Figure 1 shows the frequency with which liquid water content at Mount Washington is less than a given value during icing conditions, compared with similar data for cumuliform and stratiform clouds separately in the free air. The curve for Mount Washington is based on CONRAD'S [1948a] statistical analysis of the icing data for the season 1945-1946, and those for clouds in the free air are taken from LEWIS and KLINE [1947]. The figure shows that the water content of free-air cumuliform clouds is one and one-half to two times as great, for a given frequency of encounter, as the water content of all icing clouds at Mount Washington, while in stratiform clouds it is about two-thirds as great. Over the greater part of the frequency range a given liquid water content will be exceeded during a free-air icing encounter in cumuliform cloud about twice as frequently as during a sample icing measurement at Mount Washington. However, extreme conditions show a much greater contrast, and a water content that is exceeded ten per cent of the time in free-air cumuliform clouds is exceeded only one per cent of the time at Mount Washington. The limited amount of lifting that air may undergo before reaching the mountain summit tends to limit the greatest liquid water content that may occur.

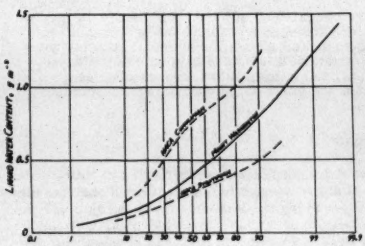


Fig. 1--Frequency of encounter of icing clouds with liquid water contents less than a given amount, for Mount Washington, for cumuliform clouds in the free air, and for stratiform clouds in the free air, 1945-1946

Drop size--Figure 2 shows the frequency with which drop size is less than a given value during observations at Mount Washington and during free-air icing encounters, according to the same sources of information used in discussion liquid water content. It shows that the drop size in the free air is one or two microns larger than at Mount Washington over most of the frequency range. The comparative frequencies with which a given drop size is exceeded differ unimportantly over most of the range, but the contrast, as with the liquid water content, is greater at the extremely large drop sizes. For example, drop diameters larger than about 32 microns are exceeded twice as often in the free air as at Mount Washington.

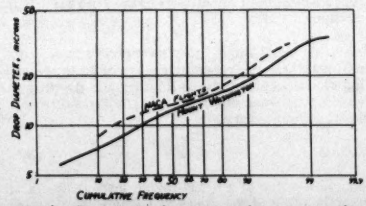


Fig. 2--Cumulative frequency of encounter of icing clouds with drop sizes less than a given size, for Mount Washington and for the free air, 1945-1946

Drop-size distribution--Figure 3 shows the frequency with which the modulus of drop-size distribution was less than a given value at Mount Washington during the 1946-1947 icing season, with comparative data from LEWIS and KLINE [1947] for free-air clouds during the same season. According to this figure, non-uniform clouds occur in the free-air with considerably greater frequency than at Mount Washington. This difference is a consequence of the forced lifting over the mountain, creating an upward current of greater strength and regularity than would be found in the free air and thus forming smaller, more uniform drops. However, the free-air data are of questionable accuracy, for the very large probable error of the free-air measurements and the skewness of the distribution would tend to displace the free-air curve fictitiously away from the

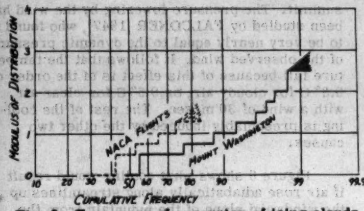


Fig. 3--Frequency of encounter of icing clouds with modulus of distribution less than a given value, for Mount Washington and for the free air, 1946-1947; the hatched areas represent the limits of capability of the measurement methods used

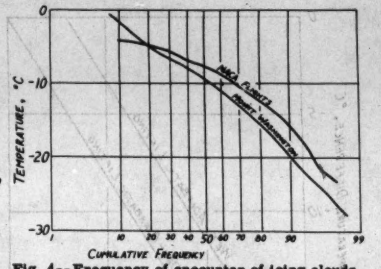


Fig. 4--Frequency of encounter of icing clouds with temperatures greater than a given value, for Mount Washington and for the free air, 1946-1947

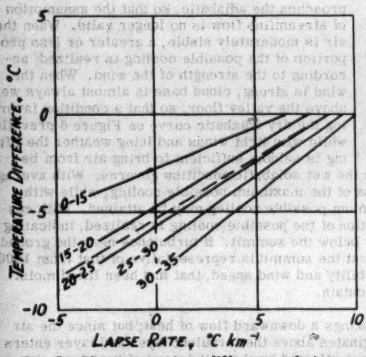


Fig. 5--The temperature differences between the summit of Mount Washington and the free air at the same altitude, as related to the wind speed in meters per second at Mount Washington and to the lapse rate between the ground and 850 mb, after BOUCHER [1949]; the dashed line is the regression of the temperature difference on the lapse rate for all cases

one for Mount Washington conditions. As is true of the liquid water content and drop size, the frequencies with which the more common values occur differ only slightly, but extremes of non-uniformity occur considerably more frequently in the free air than at Mount Washington.

Air temperature--Figure 4 shows the frequency with which icing is observed at temperatures higher than given values, at Mount Washington and in the free air for the 1946-1947 season, according to LEWIS and KLINE [1947] and CONRAD [1948b]. It shows that icing is likely to be observed at a somewhat lower temperature at Mount Washington than in the free air, but the contrast in this case does not tend to become exaggerated at extremes of low temperature. The dearth of free-air observations at temperatures just below freezing is probably due to practical difficulties of making the observations at that temperature.

Orographic effect--The influence of Mount Washington on the constitution of the clouds observed at its summit cannot, of course, be found by comparison with available free-air observations, because the latter were all made at a distance from the mountain and mostly at different altitudes. Since free-air observations near the mountain are not practicable, the orographic effect can at present be only inferred.

Whenever the air is stable, the temperature difference between the summit and the free air at the same level may be taken as an indication of the amount of lifting that the air undergoes in approaching the summit. The temperature difference has been investigated by FERGUSSON [1906, 1934] on the basis of kite soundings, by SCHELL [1935] using data obtained by airplane, and more recently by BOUCHER [1949] using for the free-air temperatures values carefully interpolated from constant-pressure aerological charts. Boucher's results are shown in Figure 5. In compiling the data he considered weather conditions associated with storms that caused icing at Mount Washington, but not fair-weather situations.

Three processes contribute to the temperature difference. They are the pressure lowering caused by the Bernoulli effect of the wind over the summit, flow of potentially colder air up the windward slope, and turbulent mixing of potentially colder air into the airstream that reaches the

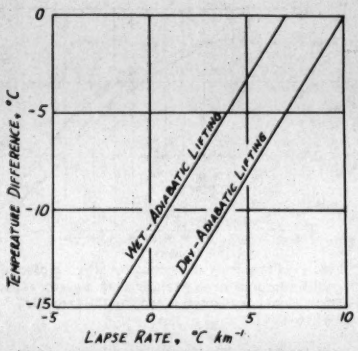


Fig. 6--The maximum temperature difference between the summit of Mount Washington and the free air at the same altitude that could be realized by wet adiabatic and dry adiabatic lifting of air from the level of the upper Connecticut valley

summit. The pressure lowering by the wind has been studied by FALCONER [1947], who found it to be very nearly equal to the dynamic pressure of the observed wind. It follows that the temperature fall because of this effect is of the order of 0.3° C for cloudy air, or 0.5° C for clear air, with a wind of 30 m/sec. The rest of the cooling is presumably induced by the other two causes.

Figure 6 shows what cooling would result if air rose adiabatically along streamlines up the windward slope of the mountain from the Connecticut Valley to the summit for dry and saturated air, respectively. Comparing this with Figure 5 we note that occasions of very slight cooling cannot be rationally treated. This is a reflection of the fact that even at low speeds, flow becomes turbulent as the lapse rate approaches the adiabatic, so that the assumption of streamline flow is no longer valid. When the air is moderately stable, a greater or less proportion of the possible cooling is realized, according to the strength of the wind. When the wind is strong, cloud base is almost always well above the valley floor, so that a condition favoring the dry adiabatic curve on Figure 6 prevails, while with light winds and icing weather the lifting is seldom sufficient to bring air from beneath the clouds up to the summit, and therefore the wet adiabatic condition governs. With average stability, light winds realize about a third or less of the maximum possible cooling, while with strong winds a half or slightly more of the maximum possible cooling may be attained. With conditions approaching instability, a greater proportion of the possible cooling is realized, indicating that the air then ascends from somewhat farther below the summit. If turbulence near the ground were neglected, it might be assumed that the air at the summit is representative of that from 1600 to 3200 ft lower in the free air, depending on stability and wind speed, that had been lifted moist-adiabatically along the windward slope of the mountain.

Turbulence, except in unstable air, always brings a downward flow of heat; but since the air reaching the point of observation apparently originates above the turbulent layer and layer enters it, it is uncertain whether the observed air is more affected by the withdrawal of heat from the upper part of the turbulent layer or by the addition of heat to the lower part. In other words, is the observed air principally potentially-warm air into which some turbulent potentially-colder air has been injected, or is it mainly turbulent air into which some potentially-warm air from aloft has been injected? The question is not important regarding the source of the cloud-forming moisture as long as lapse rates of temperature and moisture are linear, but has a bearing on the rather usual case when moisture decreases upward in a non-linear fashion.

An unavoidable effect of turbulence is that it carries liquid water downward to the ground, where it is deposited as rime on the rocks. Only a crude estimate of the effect of this loss on the liquid water content of the observed cloud can be made. During a typical storm, 1000 km of air may deposit of the order of one gram per square centimeter of rime on the ground. If we assume this water is withdrawn from a layer of cloud 50 m deep, and the deposit occurs for a kilometer before the summit is reached, the cloud will lose 0.2 gm/m^3 of water to the ground. This is roughly equivalent to the amount of water condensed out of a cloud during 1600 ft of lifting at a temperature of -10° C. If the depth is 100 m instead of 50, which might well occur in a strong wind, the loss to the rocks will be 0.1 gm/m^3. Thus it appears, as a very rough estimate, that the gain of water content by upslope lifting is offset largely if not wholly by loss to the ground. It is obvious that the loss must be somewhat proportional to the water content of the cloud, so that the above statement could not be more than an estimate of the average effect.

From a conclusion by LEWIS [1947] that when snow is falling, air must rise more than 450 ft/min before supercooled water droplets can exist, some investigators have inferred that icing clouds at Mount Washington in the presence of snow are due solely to local condensation in the updraft

over the windward slope. Lewis based his conclusion on the absence of icing observations at Mount Washington during snow when the vertical component of wind speed was less than 450 ft/min. However, since this rate of rise corresponds to a wind of only 6.7 m/sec and practical considerations make observations with the multicylinder icing meter difficult in light winds, a more valid result is obtained by considering observations of snow with and without fog during light winds. During the 1945-1946 season analyzed by Lewis, 30 observations reported snowfall with wind less than 6.7 m/sec. Measureable icing occurred with one of these, while another icing was reported too light to measure, and intermittent or continuous fog was reported on 16 more. Of the remaining 13 observations, without fog, four were of the first onset of snow, four occurred during a single stagnant air-mass condition when no fog was reported for more than nine hours before or after the snowfall, and only the remaining five represented cessations of fog during a snowstorm. Thus there were 18 observations of fog and snow with light wind against five times when fog that might otherwise have been expected was absent. The hypothesis that cloud conditions on Mount Washington during snowfall are peculiarly orographic and not representative of free-air conditions is not supported by this evidence. In a later paragraph evidence that these conditions respond largely to cyclonic controls will be presented.

Aside from the orographic effect of the individual mountain peak, the effect of the whole mountainous region on its weather is to be considered. The increased amount of ground friction and the upslope of the land both lead to widespread ascent of the air in the middle levels of the atmosphere, so that cloudiness, particularly of the stratocumulus and altocumulus types, is accentuated.

STÜVE [1937] has pointed out that orographic clouds are no different in form and constitution from other clouds, but that their distinguishing characteristic is that the locality of their prevalence is fixed by the orography. Nevertheless, there are certain forms of lenticular cloud that are so much more common in mountainous localities than elsewhere that they may be considered a local feature of the weather. These are clouds formed by the heaving of stable air strata as they flow over the rough terrain, somewhat analogous to the waves in a shallow fast-flowing river with a rough bottom. These may take the form of cap clouds remaining stationary on or over a mountain peak, or a train of clouds marking a train of wave-crests in the lee of the mountain range. At other times the air motions are more complex and induced waves may occur up to very high levels.

Occasionally the mountain summit is enshrouded by a lenticular cloud of this sort, with only a comparatively slight amount of turbulence caused by friction with the ground. On these occasions the cloud is of very uniform constitution and is generally characterized by small drop sizes. Because of the great uniformity, remarkable diffraction phenomena are sometimes visible in them. Comparable conditions occur very seldom outside orographic regions.

By far the more common type of regional orographic clouds is the stratocumulus, which occurs when the stability of the lower air is destroyed by heating from below or by turbulence. In such clouds the upflow over the mountain peak affects the constitution of the clouds somwehat, decreasing the mean drop size and making the cloud somewhat more uniform, but the water content does not greatly differ from that at other points in the cloud deck at the same level. The influence of the vertical velocities in turbulent air on the drop size spectrum is the subject of other studies by the Mount Washington Observatory [HOWELL, WEXLER, and BRAUN, 1949].

Responsiveness to non-orographic weather controls--Orographic cloud systems are generally extensions of the cloud systems associated with cyclones or with "thundery nephsystems" [SCHERESCHEWSKY and WEHRLE, 1923], forming as these systems approach, merging with them as they arrive, and dissipating some time after they have passed on. The question arises, to what extent are the clouds observed at the mountain station characteristic of the cloud system as a whole, and to what extent is their constitution determined by orographic conditions?

The frequency of fog at Mount Washington, neglecting intermittent fog (which is comparable to scattered clouds), is almost exactly the same as the frequency of ceilings below 10,000 ft at Burlington, Vermont, and Albany, New York, both of which are on the border of the area of regional orographic cloudiness, and about 20 per cent greater than the frequency of ceilings below 10,000 ft at Concord, New Hampshire, and Portland, Maine, which are lowland stations just outside the orographic region. It is therefore probably safe to say that the regional orographic effect increases the cloudiness below 10,000 ft by slightly more than 20 per cent, and that the local orography of Mount Washington causes fog there nearly as often as the regional ceiling is below 10,000 ft.

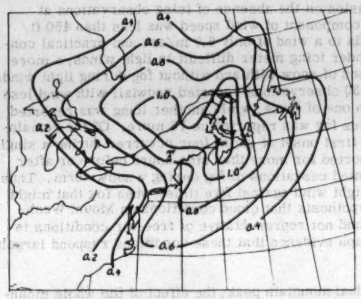


Fig. 7--The maximum liquid water content in grams per cubic meter observed at Mount Washington as related to the position of the associated cyclone center, after BOUCHER [1949]; when viewed upside down, the figure represents an approximate polar diagram of maximum liquid water content in cyclones centered at Mount Washington

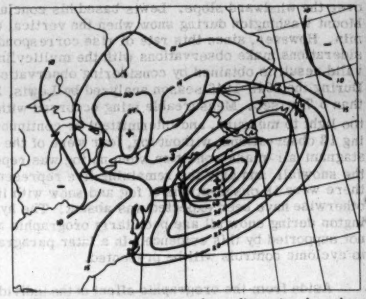


Fig. 8--The maximum drop diameter in microns observed in icing clouds at Mount Washington as related to the position of the associated cyclone center, after BOUCHER [1949]

With respect to cyclones, the question on non-orographic controls is clarified by recent studies of BOUCHER [1949, and manuscript in preparation]. Figure 7 shows the maximum liquid water content observed at Mount Washington plotted against the location of the center of the cyclone with which the cloud system was associated. The systematic concentration of the most water-productive storms in the region 200 to 300 mi northeast and north of the summit is obvious. Even more striking, as shown on Figure 8, is the concentration of storms associated with large drop sizes about the same distance to the southeast. Similar maps drawn from the data of each of two seasons separately differed so slightly from each other that the systematic nature of the distributions cannot be doubted. Since we have seen in an earlier paragraph that the average conditions on the mountain do not differ greatly from those in the free air, in comparison to the ranges of variation, we can conclude that the drop sizes and liquid water contents at Mount Washington in cyclonic cloud systems are determined principally by the non-orographic controls and are modified to a more or less determinate degree by orographic effects.

Water impingement on test objects

The icing hazard on aircraft is brought about by the action of the icing cloud on the aircraft components. It has been shown that the icing cloud on Mount Washington is comparable to that in the free air; it remains to be considered whether its action on test objects, under the influence of the natural wind, is comparable with that under conditions of flight.

In the discussion that follows, the test object considered will be a circular cylinder, since it is reasonably representative of the testing problems to be met and the theoretical basis for its treatment is firmly established [LANGMUIR and BLODGETT, 1944; TRIBUS, 1946]. The trajectory of a water droplet in a flow of air past a cylinder may be described in terms of two dimensionless parameters

$$\underline{R} = d\,\rho_a\,V/\eta \qquad \psi = 9\,\rho_a\,D/\rho_w\,d$$

where ρ_a is density of air; ρ_w, density of water; V, velocity of air; d, diameter of droplet; D, diameter of cylinder; and η, dynamic viscosity of air (used here instead of the usual μ inasmuch as μ is used otherwise). $\underline{R}$ is called the Reynolds modulus (number) and ψ the scale modulus.

No difficulty is experienced in duplicating flight values of the scale modulus at Mount Washington for the small components, which are most sensitive to the icing hazard, since the smaller value of ρ_a encountered at higher altitudes of flight can be easily compensated by increasing the size of the test object.

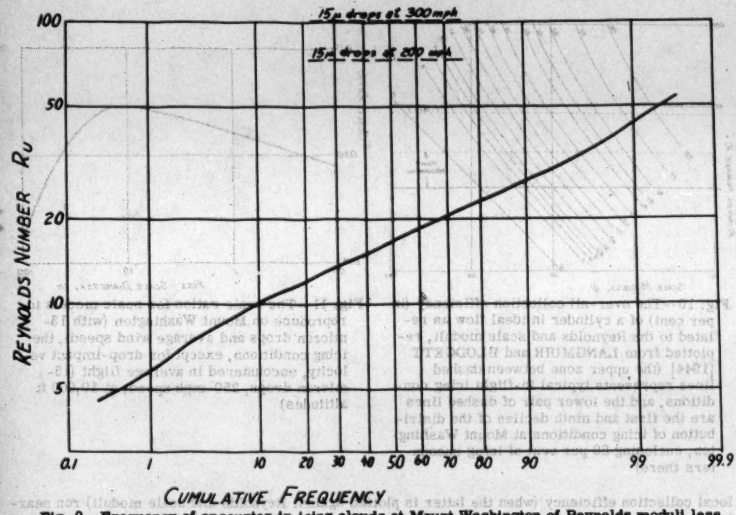


Fig. 9--Frequency of encounter in icing clouds at Mount Washington of Reynolds moduli less than given values, together with typical Reynolds moduli for in-flight icing conditions

The Reynolds modulus, however, contains the air speed and therefore has a different order of magnitude at Mount Washington as compared to flight conditions when the natural wind is used. Figure 9 shows the frequency distribution of the Reynolds modulus in the natural wind for the 1946-1947 season, together with typical flight values. It is seen that the median value of R is only about a fifth of the flight value, and that a third of the flight value is attained only about two per cent of the time. The natural wind may be increased by about 25 per cent by using a large hemispherical exposure platform, due to the Bernoulli effect, but the order of magnitude of the difference between flight and mountain values of the Reynolds modulus is not greatly affected thereby. Eighty per cent of the icing at the mountain occurs with Reynolds moduli between ten and 27. TRIBUS [1946] has concluded that, because flight values of R and ψ cannot simultaneously be duplicated in tests on models in the natural wind at Mount Washington, such tests cannot be used to study in-flight icing. Such a conclusion is justified only if it is shown that the icing process (collection efficiency and form of ice) at flight values of R is different from that at lower values. We will see in the following paragraphs whether this is so.

The over-all collection efficiency of a cylinder--The over-all collection efficiency of a cylinder is a useful gage of the icing condition experienced by the cylinder, since the over-all collection efficiency is related to the quantity of ice that is collected.

Figure 10 shows the collection efficiency of a cylinder in terms of the Reynolds and scale moduli, together with the ranges of Reynolds modulus for flight and mountain conditions. The regularity of the curvature of the lines of equal collection efficiency is a striking feature of the chart. The collection efficiencies appropriate to flight conditions at a Reynolds modulus of 80, and the manner of their change with changing scale modulus can be almost exactly duplicated at a Reynolds modulus of 20 by a scale reduction of one-third. Therefore, the collection efficiencies of aircraft components can appropriately be studied in the natural wind at Mount Washington by the use of scale models with a scale reduction of one-third to one-sixth, depending upon the Reynolds modulus expected under design operating conditions.

The local collection efficiency at the stagnation point--The local collection efficiency on the surface of a cylinder is highest at the stagnation line, so that the most severe icing condition is encountered there. This is especially true at very low efficiencies. Since the curves of equal

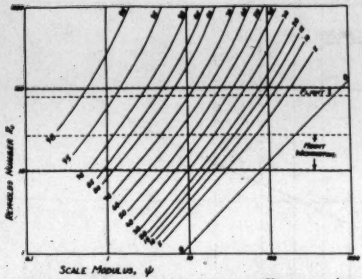


Fig. 10--The over-all collection efficiency (in per cent) of a cylinder in ideal flow as related to the Reynolds and scale moduli, replotted from LANGMUIR and BLODGETT [1944] (the upper zone between dashed lines represents typical in-flight icing conditions, and the lower pair of dashed lines are the first and ninth deciles of the distribution of icing conditions at Mount Washington, enclosing 80 per cent of icing encounters there)

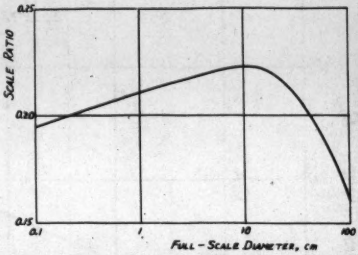


Fig. 11--The scale ratios for scale models to reproduce on Mount Washington (with 13-micron drops and average wind speed), the icing conditions, except for drop-impact velocity, encountered in average flight (15-micron drops, 250-mph speed, at 10,000 ft altitudes)

local collection efficiency (when the latter is plotted against Reynolds and scale moduli) run nearly parallel to those of equal over-all efficiency, flight values can be duplicated in the same manner as for the latter.

Maximum angular extent of impingement--The angular distance from the stagnation line at which a drop just makes grazing contact with the cylinder indicates the limit of the portion of the cylinder that must be protected from icing hazard, except for runback. There is a very close correspondence between the limiting angular distance and the over-all collection efficiency at stagnation, so that the remarks about the latter apply equally to the former.

Proportional speed of impact of drops--The speed of impact of the drops striking the surface has a bearing on the form and density of the ice collected on the surface, and on any effect that there may be from drops breaking up. Although attempts have been made to relate ice density empirically to impact velocity [LANGMUIR, 1944] and collection efficiency [LOUGHBOROUGH, 1946], no satisfactory relationship has yet been established. Laboratory studies of splash have been made by LANGMUIR [1944], but verification under flight conditions has not been accomplished.

The velocity of drop impact as a proportion of the air speed, when plotted as a function of Reynolds and scale moduli, closely resembles the over-all collection efficiency (see Fig. 10). However, since it is the absolute velocity of impact that has significance for the form and density of ice, and not the proportional velocity, in this instance flight conditions cannot be duplicated in the natural wind at Mount Washington.

Ratio scale for models--The fact that the characteristic curves for over-all (see Fig. 10) and local collection efficiency, and for maximum angular distance run very nearly parallel to one another makes it possible to construct a model with a non-linear scale reduction which will further minimize the differences between flight and mountain conditions, doing so equally for all three parameters. For a cylinder at the scale modulus determined by the median drop size at Mount Washington, the scale reduction is shown in Figure 11. The same principle may be applied to a more complex shape by appropriate selection of the linear dimension to be scaled down.

The form and density of ice

No satisfactory relationship has yet been established between the form and density of ice accumulating on an object in an icing cloud and the meteorological and dynamic parameters so far

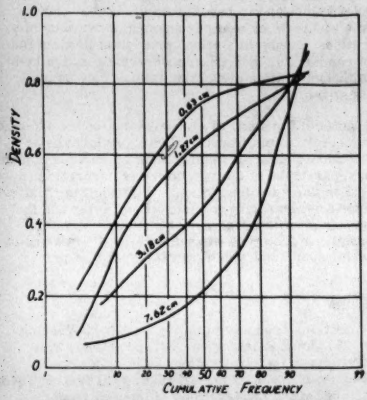


Fig. 12--Frequency of encounter at Mount Washington of ice with densities less than a given value, as related to cylinder diameter of the collecting cylinder

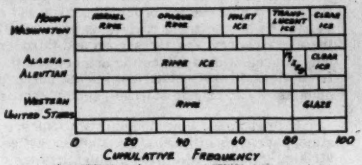


Fig. 13--Frequency of encounter of icing according to type, for the smallest cylinder of the multicylinder icing meter at Mount Washington, for pilot reports in the Alaskan-Aleutian region, and for pilot reports in the western United States

discussed, and it is therefore not possible to make a precise comparison between free-air and mountain-top icing in these respects.

The frequency of occurrence on Mount Washington of ice of various densities on cylinders of several sizes is shown in Figure 12. No comparable body of data has been published for the density of ice encountered in flight, so no direct comparison can be made. It is obvious, nevertheless, that the density on the larger cylinders is lower than most that is encountered in flight. However, since only rime has a density appreciably less than that of solid ice, something about density can be learned by considering the relative frequency with which different forms of ice occur.

Figure 13 compares the frequency with which different ice forms were encountered on Mount Washington during the 1946-1947 season with the frequencies given by SERBEIN [1945] for the Alaskan-Aleutian area and by HALLANGER [1938] for the western United States. The comparison must be made with caution, for there is no absolute standard of reference for distinguishing one form from another, and observers are likely to disagree. In particular, forms called milky and translucent ice by the Mount Washington observers, and classified as glaze because of their shiny surface, might well be reported by a pilot as rime because of their white appearance. Also, the form reported from Mount Washington is that on the smallest cylinder of the multicylinder instrument, which has much sharper curvature and hence tend more to glaze than an airplane wing. The agreement indicated by the figure is therefore as close as may be expected. Further comment on the subject has been made by LOUGHBOROUGH, GREENE, and ROUSH [1948], who found during extensive tests on boot-type de-icers at Mount Washington that "the kind and distribution of ice agree well with that obtained in flight."

Discussion

In the section on icing clouds it has been shown that icing clouds on Mount Washington are broadly representative of those encountered in flight, the differences being a small part of the range of variation and appearing significant only when the frequency of encounter of extreme conditions is considered. Until means of making routine observations of cloud constitution by radiosonde or similar methods are put into use, Mount Washington and other favorably situated mountains can be advantageously used in the study of the physics of the icing cloud and its relation to atmospheric formations and disturbances. (The obvious reservation must be made that phenomena at the top of a deep convective cell can scarcely be studied on a mountain.)

Three principal applications are at present open for data on the icing cloud. First, data are needed for the guidance and evaluation of theoretical studies of the growth and evaporation of cloud particles. Second, the data provide the material for empirical investigations such as the relation of cloud constitution and icing to air masses, fronts, cyclones of different types, and weather as observed at nearby lowland stations. In this way, it contributes to the improvement of

forecasts of the icing hazard. Third, the data may be treated statistically to provide the foundations for a climatology of icing hazards and cloud physics, and to reveal variations that may be related to longer-term variations in other climatic elements or to other physical conditions of the atmosphere. For the second and third applications, mountain stations provide at present the only source of data, since the number and mutual comparability of the few observations available from aircraft are insufficient for the purpose. Although in time mountain stations may be supplanted by radiosonde stations, such a prospect is still distant.

It is apparent that mountain stations are not suitable for study of aircraft icing under extreme atmospheric conditions or for studies that relate directly to the impact velocity of cloud drops striking objects. However, problems of the distribution of droplet impingement on various objects can be studied advantageously at mountain stations, particularly distribution of ice accretion on complex shapes such as windshields, radomes, and engine nacelles, which are difficult to treat by theoretical means. The development of instruments for measuring the intensity of icing and the physical constitution of clouds can likewise be carried on with advantage at mountain stations, avoiding the long delays usually encountered in installing prototype instruments in aircraft and obtaining performance data for them. The avoidance of space and weight limitations for experimental instruments is particularly desirable.

References

BOUCHER, R. J., A study of the meteorological conditions conducive to icing on Mount Washington, Final rep. for 1949, Contract AF 28(099)-25, Mount Washington Obs., pp. 22-43, 1949.

CONRAD, V., Second report on statistical investigations of the observations of icing at Mount Washington, N. H., Nov. 1945 through May 1946, A. F. Tech. Rep. No. 5676, pp. 134-155, 1948a.

CONRAD, V., Third report on statistical investigations of the observations of icing at Mount Washington, N. H., Nov. 1945 through May 1946, A. F. Technical Report No. 5676, p. 179, 1948b.

FALCONER, R. E., Use of pitot tube to compensate for pressure deficiency caused by wind on Mount Washington, N. H., Trans. Amer. Geophys. Union, v. 28, pp. 385-397, 1947.

FERGUSSON, S. P., Meteorological phenomena on mountain summits, Science, v. 5, pp. 672-674, 1906.

FERGUSSON, S. P., Aerological studies on Mt. Washington, Trans. Amer. Geophys. Union, 15th Annual Meeting, pp. 114-117, 1934.

HALLANGER, N. L., A study of aircraft icing, Bull. Amer. Meteor. Soc., v. 19, pp. 377-381, 1938.

HOWELL, W. E., R. WEXLER, and S. BRAUN, A theory for the drop size distribution in clouds, Final report for 1949, Contract AF 28(099)-25, Mount Washington Observatory, pp. 7-21, 1949.

LANGMUIR, I., Super-cooled water droplets in rising currents of cold saturated air, Report under Contract W-33-038 sc-65, General Electric Company, 1944.

LANGMUIR, I., and K. B. BLODGETT, A mathematical investigation of water droplet trajectories, Final report, Contract W-33-038 ac-9151, General Electric Company, 47 pp., 1944.

LEWIS, W., Icing zones in a warm front system with general precipitation, NACA Tech. Note No. 1392, 9 pp., July 1947.

LEWIS, W., and D. B. KLINE, A further investigation of the meteorological conditions conducive to aircraft icing, NACA Tech. Note No. 1424, 8 pp., Oct. 1947.

LOUGHBOROUGH, D. L., The density of ice collected on rotating cylinders, Research report No. P15.01, B. F. Goodrich Co., July 1946.

LOUGHBOROUGH, D. L., H. E. GREENE, and P. A. ROUSH, A study of wing de-icer performance on Mount Washington, Aero. Eng. Rev., v. 7, pp. 41-50, 1948.

SCHELL, I. I., Free-air temperatures from observations on mountain peaks with application to Mt. Washington, Trans. Amer. Geophys. Union, 16th Annual Meeting, pp. 126-140, 1935.

SCHERESCHEWSKY, P. L., and P. WEHRLE, Les systèmes nuageux, Paris, Office Nationale Météorologique, 1923.

SERBEIN, O. N., JR., A case study of icing in the Alaskan-Aleutian area, Weather Central, 11th Weather Region, Army Air Force, Feb. 1945.

STÜVE, G., Thermodynamik der Atmosphäre, Handbuch der Geophysik, Bd. IX, Lief. 2, Berlin, Verl. v. Gebr. Borntträger, 1937.

TRIBUS, M., The limitations and mathematical basis for predicting aircraft icing characteristics from scale model studies, Final Report of Icing Studies, University of California, 1946.

Mt. Washington Observatory,
Gorham, New Hampshire

(Manuscript received June 5, 1950; presented at the Thirty-First Annual Meeting, Washington, D. C., May 3, 1950; open for formal discussion until September 1, 1951.)

THEORY OF SURFACE-TEMPERATURE AND HEAT-TRANSFER OSCILLATIONS NEAR A LEVEL GROUND SURFACE

Heinz Lettau

Abstract--The heat-budget equation of the Earth's surface is discussed analytically under the assumptions that the radiational energy available at the ground is an harmonic time function, evaporation is constant, and heat conduction is molecular in the soil and turbulent in the atmospheric surface layer. A theoretical model of surface temperature oscillations is derived which gives the amplitudes and phase lags of both the diurnal and annual courses in terms of external conditions and the physical properties of the soil and atmosphere. Numerical verification of the theoretical results in comparison with observed findings seems to indicate that certain characteristics of the various microclimates can be explained on a physico-mathematical basis.

The heat-budget equation of the Earth's surface will be discussed in the form

$$S_0 - B_0 - L_0 - W_0 = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

The four terms of (1), which have been most thoroughly investigated by ALBRECHT [1940], are: S = net heat effect of all radiative processes, L = sensible heat transfer in the atmosphere, B = sensible heat transfer in the soil, and W = latent heat effect of phase transformations of water, that is, evaporation, sublimation, melting, freezing, or condensation. The subscript o refers to the value of a term at the ground level, z = 0, where z is the coordinate perpendicular to the ground. As is customary, we express S_0, B_0, L_0, and W_0 in units of cal cm^{-2} min^{-1} or cal $cm^{-2}sec^{-1}$.

S_0 is a rather complex quantity which includes short-wave radiation from the sun and sky, reflection from the soil and long-wave radiation from the soil and atmosphere. When the ground is solid, B consists of molecular conduction at depth -z. When the horizontal advection of heat in the atmosphere is negligible and the direction of -z coincides with that of gravity, L is the vertical heat flux at height z, normally due to turbulent conduction. W_0 is a rather complex quantity. When soil and air temperatures are above the freezing point, $W_0 \equiv E_0$, where E = vertical moisture flux at height z, multiplied by the heat of condensation. Substantially, $+E_0$ is the evaporation at the ground.

S_0 equals the net radiative heat gain of the ground. Normally, $S_0 > 0$ for day conditions and $S_0 < 0$ for night conditions. L exists for $z \gtrless 0$ and B for $z \lesseqgtr 0$ only. For convenience, we define L_0 and B_0 to be positive or negative when the Earth's surface loses or gains heat by conduction, respectively. Moreover, the sign of W_0 is positive when the ground surface loses heat because of a water phase transformation. During periods of well-pronounced diurnal variations of S_0, the sign of the ratio B_0/L_0 will be positive throughout most of the day and night. However, around sunset and sunrise, B_0/L_0 may be negative. These conditions are schematically illustrated by Figure 1.

The molecular heat conduction in the soil in cal/cm^2sec is given by

$$B = -\lambda\, \partial T/\partial(-z) = \lambda\, \partial T/\partial z \equiv \lambda T' \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

where λ = thermal conductivity expressed in cal/cm sec deg, and T = temperature in degrees Centigrade (C°). (Throughout the paper, the prime (') will be used to denote differentiation with respect to z.) Let the soil be homogeneous such that its specific heat (c, expressed in cal/gram deg), density (s, in gram/cm^3), and the thermal conductivity (λ) are independent of depth (-z, in cm). For convenience, we introduce the thermal diffusivity of the soil (cm^2/sec) as defined by Kelvin

$$\kappa = \lambda/c\,s \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

Then

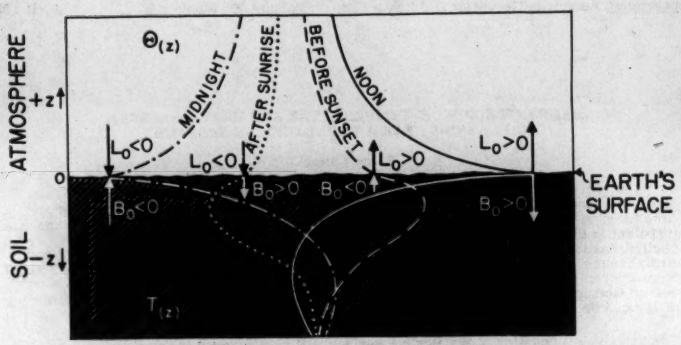


Fig. 1--Schematic types of vertical distributions of soil temperature (T) and potential temperature of the air (θ) and subsequent vertical heat fluxes (B_0,L_0) at the ground surface; a sufficiently smooth level ground is assumed so that a unique surface temperature exists ($T_0 = \theta_0$), that is, the representative temperature distribution is continuous at $z = 0$ while the vertical temperature gradient is discontinuous at $z = 0$

$$B = c_s \kappa T' \quad \text{and} \quad B_0 = c_s \kappa (T')_0 \ldots\ldots\ldots\ldots\ldots\ldots (4)$$

It is assumed that the heat conduction in the atmosphere (cal/cm^{2}sec), for $z \geqq 0$, is turbulent, and is given by the equation

$$L = -c_p \rho K \theta' \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

where c_p = specific heat of the air in cal/gram deg, ρ = density in gram/cm^3, θ = potential temperature in C°, and K = eddy diffusivity in cm^2/sec. By definition, the difference between potential and actual temperature becomes exactly zero at $z = 0$, assuming the atmospheric pressure at ground level equals 1000 mb. The main difference between (5) and (4) is caused by the thermal diffusivity term. Although κ is a physical constant, K is a function of various external conditions such as elevation, roughness character of the ground, wind force, and thermal stratification (θ'). LETTAU [1949] has defined the atmospheric surface layer, $0 \leqq z \leqq h_\theta$, as that layer where $L \approx L_0$. Normally, h_θ is of the order of several meters. In the surface layer, K in cm^2/sec may be expressed analytically by

$$K = k \overset{*}{w}_a (z + z_0) / \left\{1 + [g\theta' k^2 (z + z_0)^2] / T_m \overset{*}{w}_a{}^2\right\}^2 \ldots\ldots\ldots\ldots (6)$$

where k = von Karman's universal constant (0.45), $\overset{*}{w}_a$ = adiabatic mixing velocity in cm/sec, z_0 = roughness parameter of the ground in cm, g = acceleration of gravity (981 cm/sec^2), and T_m = mean absolute temperature of the surface layer. LETTAU [1949] has shown that $\overset{*}{w}_a$ ranges from 10 to 60 cm/sec for winds ranging from Beaufort force 1 to 5, approximately. The roughness parameter (z_0) is a function of the type of ground surface only, and ranges from 0.001 cm for exceptionally smooth surfaces (ice, concrete roads) to approximately 10 cm for ground covered with full-grown crops.

In the surface layer we have $(\overset{*}{w}_a)' = 0$ and $|(L - L_0)/L_0| \ll 1$ while θ' varies rapidly with height. LETTAU [1949] has shown that a set of the parameters $\overset{*}{w}_a$, L_0, and z_0 describes the micrometeorological conditions, inasmuch as the integration of (5), when (6) is considered, results in a unique theoretical $\theta(z)$ profile.

For given values of $\overset{*}{w}_a$, z_0, and z, (6) denotes a high value of the diffusive action of the atmosphere during superadiabatic conditions, $\theta' < 0$, and a low value during inversion conditions, $\theta' > 0$. However, one can define a low level z_1 such that for $0 \leqq z \leqq z_1 < h_\theta$ the influence of a variation of θ' on K in (6) becomes negligible. A similar statement made by PASQUILL [1949] was based on observational findings. With regard to these facts, we shall restrict the discussion of (5) to the lower parts of the surface layer, $0 \leqq z \leqq z_1$. A restatement of the definition of z_1, with the aid of (6), is

$$\left| g\theta' k^2 (z_1 + z_0)^2 / T_m \overset{*}{w}_a{}^2 \right| \ll 1 \quad \ldots\ldots (7)$$

To a sufficient degree of approximation, (6) becomes a linear function of z when $z \leqq z_1$, that is,

$$K = k \overset{*}{w}_a (z + z_0) = K'(z + z_0) \quad \ldots\ldots (8)$$

To investigate the order of z_1, we eliminate θ' in (7) with the aid of (5) and (8). Since $L \approx L_0$ for all $z \leqq h_\theta$, we obtain finally

$$z_1 \ll (c_p \rho T_m \overset{*}{w}_a{}^3 / k g \left| L_0 \right|) - z_0 \quad \ldots\ldots (9)$$

Thus, z_1 may be chosen relatively large when the wind force is large and L_0, the heating due to conduction from the air, is small. As an example, let us assume $\overset{*}{w}_a = 20$ cm/sec, $L_0 = 0.0025$ cal/cm^{2}sec = 0.15 cal/cm^{2}min, $T_m = 280°$ A when $c_p = 0.24$, and $\rho = 0.00125$. Then, (9) yields $z_1 \ll (610 - z_0)$ cm, indicating that, say below 30 cm, (8) may be replaced by (8) without producing in (5) a relative error in excess of ten per cent. The magnitude of the error can be reduced when the heights under consideration are lowered still farther.

In the thin atmospheric layer considered we may readily neglect the height variation of ρ. We shall discuss (5) finally in the form

$$L = -c_p \rho K' (z + z_0) \theta' \qquad L_0 = -c_p \rho K' z_0 (\theta')_0 \quad \ldots\ldots (10)$$

where K' depends uniquely upon the wind force, that is, K' is a constant for a given weather situation.

To combine (10) and (4) with (1), we must assume that the transformation of radiational heat takes place exactly at the Earth's surface. In other words, no sources and sinks of heat exist in the soil and the thin atmospheric layer under consideration except at the level z = 0. Physically, this assumption implies that the soil surface is relatively smooth (say, $z_0 \leqq 1$ cm) and free of vegetation since heating and cooling of plant leaves and stems would produce heat sources and sinks above the level z = 0 of a flat plain. Only then can a unique value of the surface temperature $T_0 = \theta_0$ be defined (see Fig. 1).

A characteristic of the terrestrial heat budget is that the factors of (1) are functions of time. When advectional terms are non-existent, that is, the sensible heat transfer is independent of the horizontal coordinates, the local time changes of the heat content per unit volume of the soil (csT, cal/cm^3) and of the potential heat content per volume of the air ($c_p \rho \theta$, cal/cm^3), due solely to turbulence or conduction, follow from the equation of continuity

$$(csT)^\cdot = B' \text{ (cal/cm}^3\text{sec)} \quad \ldots\ldots (11)$$

$$(c_p \rho \theta)^\cdot = -L' \text{ (cal/cm}^3\text{sec)} \quad \ldots\ldots (12)$$

(Throughout the paper the dot (·) will be used to denote partial differentiation with respect to time t.)

The combination of (11) with (4) and (12) with (10) results in

$$T^\cdot = \varkappa T'' - (T/cs)(cs)^\cdot \equiv \varkappa T'' - T(\log_e cs)^\cdot \text{ (C°/sec)} \quad \ldots\ldots (13)$$

$$\theta^\cdot = K\theta'' + K'\theta' - \theta(\log_e c_p \rho)^\cdot \text{ (C°/sec)} \quad \ldots\ldots (14)$$

When the local time changes of cs and $c_p\rho$ are negligible, (13) and (14) become the well-known partial differential equations of thermal diffusion. More useful for the analysis of the heat budget equation is a similar system of equations obtained by differentiating (11) and (12) once with respect to z, where B and L are the dependent variables. Since it is permissible to change the order of differentiation, we have

$$[(csT)^\cdot]' = [(csT)']^\cdot \qquad [(c_p \rho \theta)^\cdot]' = [(c_p \rho \theta)']^\cdot \quad \ldots\ldots (15)$$

Making the assumptions of homogeneity of soil and air, that is, $(cs)' = (c_p \rho)' = 0$, it follows, with the aid of (15), (12), (11), (10), (5), and (4)

$$B^\cdot = \varkappa B'' + B(\log_e \varkappa)^\cdot \text{ (cal/cm}^2\text{sec}^2\text{)} \quad \ldots\ldots (16)$$

$$L^{\cdot} = K L'' + L (\log_e K)^{\cdot} \ (cal/cm^2 sec^2) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (17)$$

For the most general solution of the problem of time-varying heat-budget terms near the ground, an equation for $W^{\cdot}$ should be obtained. Since it proves to be difficult to establish a relation for $W^{\cdot}$ similar to $B^{\cdot}$ and $L^{\cdot}$, the problem is simplified by assuming that $W_0 = E_{00}$, where E_{00} is evaporation or condensation at the ground and at time $t = 0$. Thus W_0 is independent of time. E_{00} is equal to zero when the soil is dry. Since moisture variations will be the most important cause of time changes of the physical soil properties c, s, λ, or κ, it seems appropriate to assume $\kappa^{\cdot} = 0$ and $(cs)^{\cdot} = 0$ when $W_0 = E_{00}$ = constant.

In (8), the eddy diffusivity of the lowest atmospheric layers depends upon the parameters $\overset{*}{w}_a$ and z_0. Since roughness is a physical property of the ground, z_0 will not depend upon time when the effects of plant growth and of varying snow cover can be disregarded. In order to have $K^{\cdot} = 0$ in (17), we assume $\overset{*}{w}_a$ = constant. This assumption corresponds to that of a steady wind force [LETTAU, 1949].

The mathematical problem is reduced to the solution of the following two interdependent systems of differential equations

$$B^{\cdot} = \kappa B'' \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (18a)$$

$$L^{\cdot} = K L'' = K' (z + z_0) L'' \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (18b)$$

and/or

$$T^{\cdot} = \kappa T'' \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (19a)$$

$$\theta^{\cdot} = K \theta'' + K' \theta' = K' (z + z_0) \theta'' + K' \theta' \quad \ldots\ldots\ldots\ldots\ldots\ldots (19b)$$

where K', z_0, and κ are constants. As a consequence of the assumption $W_0 = E_{00}$ we have $W^{\cdot} = 0$ for $0 \leqq z \leqq z_1$, whereupon (1) becomes $S_0 = E_{00} + L_0 + B_0$ thus determining the boundary conditions of simultaneous solutions of (18a,b) at $z = 0$ in terms of S_0 (t).

The intensity of short-wave radiational energy at the ground follows from external conditions, such as the rotation of the Earth and its position relative to the sun, the optical properties of the atmosphere and the albedo of the ground surface. Long-wave radiation terms of S_0 depend upon the absolute temperature of the soil and air and the amount of water vapor and dust in the atmosphere.

ALBRECHT'S [1940] analysis of the terrestrial S_0 terms has shown that short-wave radiation largely determines the diurnal and annual variations of S_0, especially in temperate latitudes. Disregarding the relatively small effect which T_0 variations have on S_0 we confine the theoretical investigation to forced harmonic S_0 oscillations which result from the Earth's rotation and revolution and the position of the surface area exposed to the sun.

Summarized, the following boundary and initial conditions must be satisfied:

(I) For large heights and depths, L and B approach zero at all times.

(II) For $z = 0$, temperature is continuous at all times,

$$T_0 = \lim_{-z \to 0} T(-z) = \lim_{z \to 0} \theta(z) = \theta_0 \quad \ldots\ldots\ldots\ldots\ldots\ldots (20)$$

(III) At $z = 0$, S_0 is a given harmonic function of time,

$$S_0 = S_{00} + s_0 e^{-i\nu t} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (21)$$

where S_{00} is a constant; s_0, the amplitude of a harmonic oscillation of frequency ν (sec^{-1}); and $i = \sqrt{-1}$. We are mainly interested in the diurnal and annual S_0 oscillations, that is, in the two ν values $\nu_d = 2\pi/86{,}400$ and $\nu_a = \nu_d/365$. In (21) and the following equations, t denotes true local solar time and season.

(IV) $W_0 = E_{00}$, independent of time.

(V) At z = 0,

$$S_0(t) - E_{00} = \left\{B(-z,t) + L(z,t)\right\}_0 \equiv B_0(t) + L_0(t) \quad \ldots\ldots\ldots\ldots\ldots (22)$$

With regard to (22), let

$$B_0 = B_{00} + b_0\, e^{-i(\nu t + \beta)} \quad \ldots\ldots\ldots\ldots\ldots\ldots (23a)$$

and

$$L_0 = L_{00} + a_0\, e^{-i(\nu t + \alpha)} \quad \ldots\ldots\ldots\ldots\ldots\ldots (23b)$$

where β and α are constants which denote that the phase of the B_0- and L_0-oscillations of amplitudes b_0 and a_0, respectively, might differ from each other and from that of the primary S_0 wave. Since B_{00} and L_{00} are independent of both variables t and z, we can write (18a,b) in terms of $(B - B_{00})$ and $(L - L_{00})$.

A solution of (18a) which satisfies condition I and (23a) is

$$B(z,t) - B_{00} = (B_0 - B_{00})\, e^{(1-i)z\sqrt{\nu/2\kappa}} \quad \ldots\ldots\ldots\ldots\ldots (24)$$

Equation (24) is well known in the theory of heat conduction in homogeneous solids and yields $B(z,t)$ as a depth-varying harmonic oscillation of the original frequency, the amplitude of which decreases exponentially, while the phase shows a constant rate of retardation with -z. Reference can be made to INGERSOLL [1948, p. 46].

To solve (18b) we introduce a new independent variable x, which is a complex number and related to the independent variable z as follows

$$x = 2\sqrt{i\,\nu\,(z + z_0)/K'} \qquad x_0 = 2\sqrt{i\,\nu\, z_0/K'} \quad \ldots\ldots\ldots\ldots\ldots (25a)$$

$$x' = x/2\,(z + z_0) \qquad x'' = -\,x/4\,(z + z_0)^2 \quad \ldots\ldots\ldots\ldots\ldots (25b)$$

With the aid of (25a,b) and (23b), (18b) transforms into

$$d^2\,(L - L_{00})/d\,x^2 - (1/x)\,d\,(L - L_{00})/d\,x + (L - L_{00}) = 0. \quad \ldots\ldots\ldots\ldots (26)$$

Equation (26) is satisfied by Bessel functions of order one. Among the Bessel functions only those introduced by Hankel are distinguished by the fact that they converge to zero for an infinite complex argument x [JAHNKE and EMDE, 1938, p. 133]. Reference can also be made to HAURWITZ [1936]. Thus, a solution of (18b) which satisfies condition I and (23b) is

$$L(z,t) - L_{00} = (L_0 - L_{00})\, x\, H_1(x)/x_0\, H_1(x_0). \quad \ldots\ldots\ldots\ldots\ldots (27)$$

where H_1 denotes a Hankel function of order one.

When checking the solution (27), one must use the following relations from the theory of the Bessel functions

$$d\,H_1(x)/d\,x = H_0(x) - (1/x)\,H_1(x) \quad \ldots\ldots\ldots\ldots\ldots (28)$$

$$d\,H_0(x)/d\,x = -\,H_1(x). \quad \ldots\ldots\ldots\ldots\ldots (29)$$

where $H_0(x)$ denotes a Hankel function of order zero.

To satisfy condition II, we may either solve (19a,b) directly or transform solutions (24) and (27) into terms of T and θ by means of (2) and (5), or (11) and (12). Selecting the last one of these possibilities, we obtain

$$T(z,t) = T(z,0) + (1/cs)\int_0^t B'\,dt \quad \ldots\ldots\ldots\ldots\ldots (30)$$

$$\theta(z,t) = \theta(z,0) + (1/c_p\rho)\int_0^t L'\,dt \quad \ldots\ldots\ldots\ldots\ldots (31)$$

With the aid of (23a) and (24), (30) becomes

$$T(z,t) = T(z,0) + [(1+i)/cs\sqrt{2\nu\kappa}]\left\{B(z,t) - B(z,0)\right\} \quad (32)$$

or at $z = 0$,

$$T(0,t) \equiv T_o = T_{oo} + [(1+i)/cs\sqrt{2\nu\kappa}]\,(B_o - B_{oo}) \quad (33)$$

In a corresponding manner, with the aid of (23b), (25a,b), (27), and (28), (31) becomes at height z

$$\theta(z,t) = \theta(z,0) + (\kappa'/c_p\ \rho\ i\nu)\,[H_o(x)/H_1(x)]\left\{L(z,t) - L(z,0)\right\} \quad (34)$$

or at $z = 0$,

$$\theta(0,t) \equiv \theta_o = \theta_{oo} + [(1-i)/c_p\,\rho\sqrt{2\nu K_o}]\,[H_o(x_o)/H_1(x_o)]\left\{L_o - L_{oo}\right\} \quad (35)$$

In (25a) we define a real height function ϵ as being equal to $x/\sqrt{i}$, or

$$\epsilon = 2\sqrt{\nu(z+z_o)/K'} = x/\sqrt{i} \qquad \epsilon_o = 2\sqrt{\nu z_o/K'} = x_o/\sqrt{i} \quad (36)$$

Let "magn" stand for "the order of magnitude of". Excluding extremely light wind speeds and large roughness parameters, we have

$$\begin{aligned} \text{magn } K' &= \text{magn } \overset{*}{w}_a = 10^1 \text{ cm/sec} \\ \text{magn } z_o &= 10^{-3} \text{ to } 1.0 \text{ cm} \\ \text{magn } (z_1+z_o) &= 10^2 \text{ cm} \\ \text{magn } \nu_a &= 10^{-7} \text{ sec}^{-1} \\ \text{magn } \nu_d &= 10^{-4} \text{ sec}^{-1} \end{aligned}$$

Consequently, with the aid of (36)

$$\text{magn } \epsilon_o = 10^{-3} \text{ to } 10^{-6}$$

and, recalling that $0 \leqq z \leqq z_1$,

$$\text{magn } \epsilon < 10^{-2} \quad \text{or} \quad 0 < \epsilon < 0.01$$

From the theory of Bessel functions [JAHNKE and EMDE, 1938], it follows that, for $\epsilon \ll 1$, the Hankel functions of the first kind degenerate into logarithmic terms. When $0 \leqq \epsilon \leqq 0.01$ we have to a sufficient degree of approximation

$$H_o^{(1)}(\epsilon\sqrt{i}) \approx 1/2 + i\,(2/\pi)\log_e 0.8905\,\epsilon \quad (37)$$

$$H_1^{(1)}(\epsilon\sqrt{i}) \approx -2\sqrt{i}/\pi\epsilon = -(1+i)\sqrt{2}/\pi\epsilon \quad (38)$$

where $H_n^{(1)}$ denotes a Hankel function of the first kind of order n. For the sake of brevity, we introduce as an abbreviation

$$\left.\begin{aligned} j &= -(2/\pi)\log_e \epsilon_o\, 0.8905 \\ &= -2\,(\log_e 0.8905 + \log_e 2)/\pi + (\log_e k + \log_e \overset{*}{w}_a - \log_e z_o - \log_e \nu)/\pi \end{aligned}\right\} \quad (39a)$$

$$J = j - (1/\pi)\log_e (z+z_o)/z_o \quad (39b)$$

Equations (36) and (8) were considered in (39a). The symbol j is a dimensionless function of the turbulence parameters $\overset{*}{w}_a$ and z_o, and of frequency ν. Let the subscripts d and a refer, in (39a,b), to the diurnal and annual waves, respectively. Thus

$$j_a = j_d - (1/\pi)\log_e (\nu_a/\nu_d) = j_d + 1.88 \quad (40)$$

Table 1--The symbol j_d, computed from (39a), as a function of adiabatic mixing velocity $\overset{*}{w}_a$ and roughness parameter of the ground z_o

z_o	$\overset{*}{w}_a$ in cm/sec			
	10	20	30	40
cm				
10	2.92	3.14	3.27	3.36
1	3.65	3.87	4.00	4.09
0.1	4.39	4.61	4.75	4.83
0.01	5.12	5.34	5.47	5.56
0.001	5.85	6.07	6.20	6.29

Table 1 shows numerical values of j_d for various $\overset{*}{w}_a$ and z_o. It can be noted from this table and (40) that wide ranges of the parameters $\overset{*}{w}_a$, z_o, and ν produce relatively small effects on the value of j.

With the aid of (39a), (38), and (37), we obtain from (35)

$$\theta_o = \theta_{oo} + (\pi/K' c_p \rho)\,(j + 1/2)\,(L_o - L_{oo}) \quad \ldots (41)$$

Equation (20), which may be termed the uniqueness condition of surface temperature, implies that in (33) and (41)

$$T_o = \theta_o \quad \text{and} \quad T_{oo} = \theta_{oo} \quad \ldots\ldots\ldots (42)$$

Upon writing

$$T_o = T_{oo} + \Delta T_o\, e^{-i(\nu t + \gamma)} \quad \ldots\ldots\ldots\ldots\ldots\ldots (43)$$

where ΔT_o = amplitude and γ = phase constant of the surface temperature oscillation of frequency ν, it follows from (42), (41), (33), (32), and (23a,b) that

$$(\pi/K' c_p \rho)\,(j + 1/2)\,a_o\, e^{-i(\nu t + \alpha)} = [(1 + i)/cs\sqrt{2\nu\kappa}\,]\, b_o\, e^{-i(\nu t + \beta)} = \Delta T_o\, e^{-i(\nu t + \gamma)}. \quad (44)$$

Real and imaginary parts of these three terms must satisfy relation (44) simultaneously at any time t. Thus, we can choose t = 0 in order to obtain from (44) the following equations

$$\Delta T_o = (\pi a_o/K' c_p \rho)\sqrt{j^2 + 1/4} \quad \ldots\ldots\ldots\ldots (45a)$$

$$\Delta T_o = b_o/cs\sqrt{\nu\kappa} \quad \ldots\ldots\ldots\ldots\ldots\ldots (45b)$$

$$\tan\gamma = (j \sin\alpha - 0.5\cos\alpha)/(j\cos\alpha + 0.5\sin\alpha) \quad \ldots\ldots\ldots\ldots (46a)$$

$$\tan\gamma = (\sin\beta - \cos\beta)/(\cos\beta + \sin\beta) \quad \ldots\ldots\ldots\ldots (46b)$$

Thus

$$b_o/a_o = (\pi cs/K' c_p \rho)\sqrt{\nu\kappa(j^2 + 1/4)} \equiv R. \quad \ldots\ldots\ldots\ldots (47)$$

and

$$\tan(\beta - \gamma) = 1 \qquad \beta = \gamma + \pi/4 \quad \ldots\ldots\ldots\ldots (48)$$

$$\tan(\alpha - \gamma) = 1/2j \qquad \alpha = \gamma + \tan^{-1}(1/2j) \quad \ldots\ldots\ldots\ldots (49)$$

Several very interesting conclusions can be drawn from the above results. For instance, (47) shows that R, which is the amplitude ratio of B_o and L_o oscillations of a given period, is a unique function of soil and atmospheric properties and frequency ν. Since j varies proportional to $\log_e \nu$, it follows from (47) that R_d will be considerably larger than R_a, provided $\overset{*}{w}_a$ and z_o like κ, c, and s remain the same for both diurnal and annual S_o variations.

Regardless of the frequencies and amplitudes of B_o oscillations, the phase lag of T_o against B_o waves, (48), is exactly equal to $\pi/4 = 45°$, that is, 3 hours for diurnal, and 1.5 months for annual oscillations. In noteworthy contrast, the phase lag of the T_o against the L_o wave depends upon j, that is, upon $\overset{*}{w}_a$, z_o, and ν (see (39a)). Table 1 shows that, normally, this phase lag will be considerably smaller than 45°. As an example, we assume $\overset{*}{w}_a$ = 20 cm/sec and z_o = 0.1 cm; then, Table 1 gives j_d = 4.61 and from (40) j_a = 6.49. With the aid of (49), $(\alpha - \gamma)$ becomes 6.2° = 0.41 hour = 25 min for diurnal, and 4.4° = 0.15 month = 4.5 days for annual oscillations.

It should be emphasized that the above results rest entirely on the assumptions that heat conduction in the soil is molecular, that is, $\kappa' = 0$, and that in the atmosphere, for any $z \geqq 0$, the heat exchange takes place purely by means of turbulence, that is, $K' \neq 0$. If the ground were covered by a "laminar sublayer", that is, a layer of air of small but finite thickness in which heat is conducted solely by way of molecular action, then K' would equal zero in this sublayer. Hence, in close proximity to the ground, solutions (27) and (41) would become substantially equivalent to solutions (24)

and (33) with the constant molecular thermal diffusivity of air in place of κ. All heat flowing through the surface layer would be determined by heat conduction in the underlying laminar sublayer. The amplitude ratio B_0/L_0 would be equal to a physical constant and no phase lag could occur between the L_0 and B_0 wave at the surface. This is contradictory to experience as shall be demonstrated at the end of the paper. One might say that observed amplitude ratios and phase differences between the L_0 and B_0 waves provide strong evidence against the concept of a "laminar sublayer" over bare natural ground having ordinary smoothness.

In the above discussions only the phase differences $(\alpha - \gamma)$, $(\beta - \gamma)$, and $(\alpha - \beta)$, which are consequences of the uniqueness of surface temperature, were considered. In addition, (1) or (22) can be used to relate α, β, and γ to the phase of the primary S_0 oscillation, that is, to express the three phase constants in true local time and season. We obtain with the aid of (21), (22), (23a), and (23b),

$$S_{00} - B_{00} - L_{00} - E_{00} = - s_0 e^{-i\nu t} + a_0 e^{-i(\nu t + \alpha)} + b_0 e^{-i(\nu t + \beta)} \quad \ldots\ldots (50)$$

The left-hand side of (50) equals a real constant. Thus, choosing $t = 0$, we find from the imaginary part of the right-hand side

$$a_0 \sin \alpha + b_0 \sin \beta = 0 \quad \ldots\ldots (51)$$

whereupon (51, (49), (48), and (47) yield

$$\tan \gamma = - [R\sqrt{2}/2 + \sin (\tan^{-1} 1/2j)]/[R\sqrt{2}/2 + \cos (\tan^{-1} 1/2j)] \quad \ldots\ldots (52)$$

From the real part of the right-hand side of (50) we obtain with the aid of $(\beta - \alpha) = (\pi/4 - \tan^{-1} 1/2j)$ [see (49) and (48)]

$$a_0 = (S_{00} + s_0 - B_{00} - L_{00} - E_{00})/\sqrt{1 + R^2 + 2R \cos (\pi/4 - \tan^{-1} 1/2j)} \quad \ldots\ldots (53)$$

and, finally, with the aid of (45a)

$$\Delta T_0 = [\pi (s_0 + S_{00} - B_{00} - L_{00} - E_{00}) \sqrt{j^2 + 1/4}]/K' c_p \rho \sqrt{1 + R^2 + 2R \cos (\beta - \alpha)} \quad (54)$$

where R, j, and $K' = k\overset{*}{w}_a$ follow from physical parameters including ν when $s_0 + S_{00} - B_{00} - L_{00} - E_{00}$ represents the external conditions of the problem.

Equations (45a) to (54) enable us to obtain numerically the amplitude and the phase constant of surface temperature, and the portion of heat transferred into the soil and atmosphere. Thus, on the basis of defined external factors (harmonically oscillating radiational heat, thermodynamical, dynamical and geometrical properties of the soil and atmosphere) the main characteristics of the thermal microclimate of the ground can be predicted. It may be noted that for mean annual variations at a fixed point of the Earth's surface, B_{00} and L_{00} is rather small as compared with S_{00} when E_{00} is approximately equal to S_{00}. However, when monthly means of diurnal variations or mean diurnal variations of selected days are investigated, the annual courses of B_0 and L_0 produce B_{00} and L_{00} terms of diurnal waves. Examples will be discussed at the end of the paper.

Historically, it is noteworthy that SCHMIDT [1918] derived a simplified theory of the different fractions of the total heat which can be utilized by the ground and the air, respectively. Schmidt assumed a constant and rather large value of the thermal eddy diffusivity of the air, that is, $K = K_{00} = 40{,}000$ cm^2/sec, in (5). Consequently, a zero value of the phase difference $(\beta - \alpha)$ results, while the ratio B_0/L_0, although dependent on the soil constants, was found to be independent of the frequency. Schmidt's theory was discussed by GEIGER [1942]. In spite of its shortcomings it provided an interesting explanation of climatic and microclimatic differences, especially between continental and maritime types of diurnal temperature oscillations due to the extreme range of thermal diffusivity between various types of solid ground and the turbulent ocean.

Equations (45a) to (54) enable us to discuss existing climatic differences in more detail. Listed in Table 2 are the physical constants employed in computing the results shown in Tables 3 and 4. We chose $\overset{*}{w}_a = 20$ cm/sec and $z_0 = 0.1$ cm. Such values correspond to an average wind speed and a roughness character similar to that of desert plains, short cut lawn or the ocean surface. The wind speed u_a in the adiabatic surface layer at height z is obtained with the aid of the Prandtl formula, $u_a = (\overset{*}{w}_a/k) \log_e (z + z_0)/z_0$; for example, $u_a = 3.4$ m/sec when $\overset{*}{w}_a = 20$ cm/sec, $k = 0.45$, $z_0 = 0.1$ cm, and $z = 200$ cm [LETTAU, 1949].

Table 2--Thermal conductivity λ, specific heat c, density s, and thermal diffusivity for various ground types and for still water and air

Ground type	λ	c	s	κ	Reference
	cal/deg cm sec	cal/deg g	g/cm^3	cm^2/sec	
Concrete	0.0058	0.22	2.47	0.0107	Ingersoll, 1948
Quartz sand (medium fine, dry)	0.00063	0.19	1.65	0.0020	Ingersoll, 1948
Sandy clay (15 pct moisture)	0.0022	0.33	1.78	0.0037	Ingersoll, 1948
Clayland pasture	0.0067	cs = 0.56		0.0012	Pasquill, 1949
Snow	0.00027	cs = 0.10		0.0027	Geiger, 1942
Turbulent water (ocean)[a]	1 to 100	1.0	1.0	1 to 100	Schmidt, 1918
Still water	0.0015	1.0	1.0	0.0015	Geiger, 1942
Still air	0.00005	0.24	0.0012	0.16	Geiger, 1942

[a]Solution (24) is valid for the turbulent ocean only when the apparent (that is, eddy) λ-values are independent of depth.

Table 3--Diurnal waves. Theoretical values of R_d from (47) and the hour of the maximum value of S_o, T_o, B_o, and L_o oscillations in true local time when $\bar{w}_a$ = 20 cm/sec and z_o = 0.1 cm; the units of the thermal property parameter $cs\sqrt{\kappa} = \sqrt{cs\lambda}$, from Table 2, are cal/(cm^2 deg sec$^{1/2}$)

Ground type	$\sqrt{cs\lambda}$	R_d	S_o	T_o	B_o	L_o
			h m	h m	h m	h m
Concrete	0.0566	2.56	12 00	14 18	11 18	13 53
Sandy clay	0.0359	1.65	12 00	14 02	11 02	13 37
Clay land	0.0199	0.92	12 00	13 39	10 39	13 14
Snow	0.0052	0.24	12 00	12 54	09 54	12 29
Ocean, λ = 1	1	46	12 00	14 58	11 58	14 33
Ocean, λ = 100	10	460	12 00	14 59	11 59	14 34

Table 4--Annual waves. Theoretical values of R_a from (47) and the date of the maximum value of S_o, T_o, B_o, and L_o oscillations for various ground types when $\bar{w}_a$ = 20 cm/sec and z_o = 0.1 cm

Ground type	R_a	S_o	T_o	B_o	L_o
Concrete	0.188	June 23	July 4	May 19	June 29
Sandy clay	0.121	June 23	July 2	May 17	June 27
Clay land	0.067	June 23	June 30	May 15	June 25
Snow	0.018	June 23	June 28	May 13	June 23
Ocean, λ = 1	3.4	June 23	July 28	June 13	July 23
Ocean, λ = 100	33.8	June 23	Aug. 6	June 23	Aug. 1

Let us define an equable microclimate as one characterized by a relatively small amplitude of surface temperature when the sum $S_o + S_{oo} - B_{oo} - L_{oo} - E_{oo}$ is a constant. For given atmospheric conditions, ground types having a large value of the thermal property parameter $cs\sqrt{k} \equiv \sqrt{cs\lambda}$ tend toward an equable microclimate. The portion of radiational energy utilized in heating the air is small compared with that utilized in heating the soil, and the time lag between the occurrence of strongest heating by radiational energy and the maximum value of surface temperature is relatively long, that is, the value of R is relatively large. For a given soil type, atmospheric conditions having a relatively large value of $\bar{w}_a = K'/k$ produce also a microclimate of moderate extremes. It appears noteworthy that the geometrical roughness character of the ground has similar effects inasmuch as R is relatively large when z_o is relatively small while, concurrently, j is relatively large. This is related to the theoretical result obtained by LETTAU [1949] that the vertical temperature gradient near the surface increases when z_o decreases.

Owing to the effect of frequency ν on R (see (47)) the microclimate for a given ground type and atmospheric conditions is relatively milder for diurnal than for annual oscillations of incident radiational energy. For example, in the extremely mild climate near the ocean surface, we should expect the annual range of surface temperature to be considerably larger than the diurnal range, even though $(s_o)_a \approx (s_o)_d$. When it is assumed that $K'_a = K'_d$ and $S_{oo} = B_{oo} + L_{oo} + E_{oo}$, (54) yields

$$\frac{(\Delta T_o)_a}{(\Delta T_o)_d} = \frac{(s_o)_a}{(s_o)_d}\sqrt{\frac{(1 + R_d^2 + 2\,R_d \cos(\beta_d - \alpha_d))(j_a^2 + 0.25)}{(1 + R_a^2 + 2\,R_a \cos(\beta_a - \alpha_a))(j_d^2 + 0.25)}} \quad \ldots\ldots\ldots (55)$$

Table 5--Theoretical amplitude ratio of mean annual and average diurnal oscillations of surface temperature for various ground types when $\overset{*}{w}_a = 20$ cm/sec, $z_o = 0.1$ cm, and $(s_o)_a = (s_o)_d$

Ground type	R_a	R_d	$(\Delta T_o)_a/(\Delta T_o)_d$
Concrete	0.188	2.56	4.1
Sandy clay	0.121	1.65	3.2
Clay land	0.067	0.92	2.4
Snow	0.018	0.24	1.7
Ocean, $\lambda = 1$	3.4	46	15.5
Ocean, $\lambda = 100$	33.8	460	18.7

In (55), $(\Delta T_o)_a$ is the mean amplitude of the annual course and $(\Delta T_o)_d$ the annual average of the diurnal amplitudes of surface temperature. Numerical examples are listed in Table 5. It follows from ALBRECHT'S [1940] data that $(s_o)_a/(s_o)_d$ equals approximately 0, 1/2, and 1 near the equator, 45° and 60° north latitude, respectively.

Theoretically, the extreme ratio of mean annual to diurnal amplitudes should be found at the ocean surface, where it might be 19:1 as follows from Table 5. On the basis of measurements SVERDRUP [1942] states that the range of the diurnal variation of sea surface temperature can be represented, on the average, by a sine curve with maximum values between 14h 30m and 15h 00m (compare Table 3) and a range of less than 0.4 C°. In remarkable contrast, annual ranges of surface temperature are 4 to 8 C° in temperate latitudes. It might appear appropriate to try a new analysis of the sea surface temperature observations in the light of the above-discussed theoretical developments when allowance is made for the physical conditions near the ocean surface, especially the effect of currents.

The checking of the theoretical results as discussed below is based on ALBRECHT'S [1940] investigation of the diurnal and annual variations of the components of the heat-budget equation (1) at the Potsdam Observatory (see Fig. 2). The graph shows that for annual variations $R_a \approx 0.2$, for diurnal variations in June $R_d \approx 2$, rather close to what one might expect from the theoretical values of Tables 3 and 4 for sandy soil. Apparently, the above-assumed values of $\overset{*}{w}_a$ and z_o are not too far from the true average conditions at the Potsdam Observatory. The annual and especially the diurnal L_o and B_o oscillations indicate that the observed phase lags fit into the theoretical picture, too. For comparison, the annual T_o wave and the diurnal T_o variation for the month of June are represented in Figure 2. One sees that $(\Delta T_o)_a/(T_o)_d$ for June is approximately unity. Albrecht's analysis of the radiational terms resulted in $(s_o)_a/(s_o)_d$, June $\approx$ 0.3. Thus, the agreement with the theoretical result, (55), is satisfactory inasmuch as Table 5 shows that for sandy soil the square root in (55) equals approximately 3. However, the deviations of the observed hourly and monthly B_o and L_o values from the sine waves are rather large. This may be caused by neglecting the diurnal and annual W_o variations while the soil properties are affected during the course of the seasons by snow and rain. The theory in its present phase of development appears mainly to be applicable to the dry climate of deserts. Examples of observed S_o, B_o, L_o, E_o, and T_o variations in the Gobi Desert can be found in the article by LETTAU [1949].

The use of the theory for predicting the diurnal course of surface temperature of dry ground will be demonstrated with the aid of Figure 3. This graph shows the B_o and L_o variations constructed for the arbitrarily assumed diurnal sine wave of surface temperature with an amplitude of $\Delta T_o = 10$ C°, from six hours before to six hours after the time of maximum value of surface temperature. The true local time of this event follows from (52). Reference can also be made to Table 3, which is based on the special values $\overset{*}{w}_a = 20$ cm/sec, and $z_o = 0.1$ cm. Let us consider a dry concrete surface where $W_o = 0$, and let us assume, as an example, $S_o = 0.01$ cal/cm^{2}sec = 0.60 cal/cm^{2}min at the time when T_o has its maximum value. From Figure 3, we read $B_o^* = 0.20$ and $L_o^* = 0.30, 0.21, 0.16, 0.11$, and 0.04 cal/cm^{2}min for $\overset{*}{w}_a$ and z_o values as indicated in the graph. These values are tentative as indicated by (*) and are valid for the tentative temperature amplitude $\Delta T_o = 10$ C°. To satisfy (1) when $W_o = 0$, we must have $\Delta T_o/\Delta T_o^* = (L_o + B_o)/(L_o^* + B_o^*)$ and, therefore, $\Delta T_o = 12.0, 14.6, 16.7, 19.3$, and 25.0 C°, respectively, since L_o like B_o is proportional to ΔT_o, as follows from (45a,b), and the sum $B_o + L_o$ equals S_o which was assumed to be 0.60 cal/cm^{2}min. This example illustrates that for a given soil type the tendency is toward a microclimate of greater extremes when the wind force and/or the roughness parameter decrease. Computations of this kind appear useful for establishing theoretical climatology on a physico-mathematical basis.

In Figure 3 and the above example, we considered the diurnal oscillations of B_o and L_o without taking into account B_{oo} and L_{oo} terms. This is permissible for the annual means of diurnal

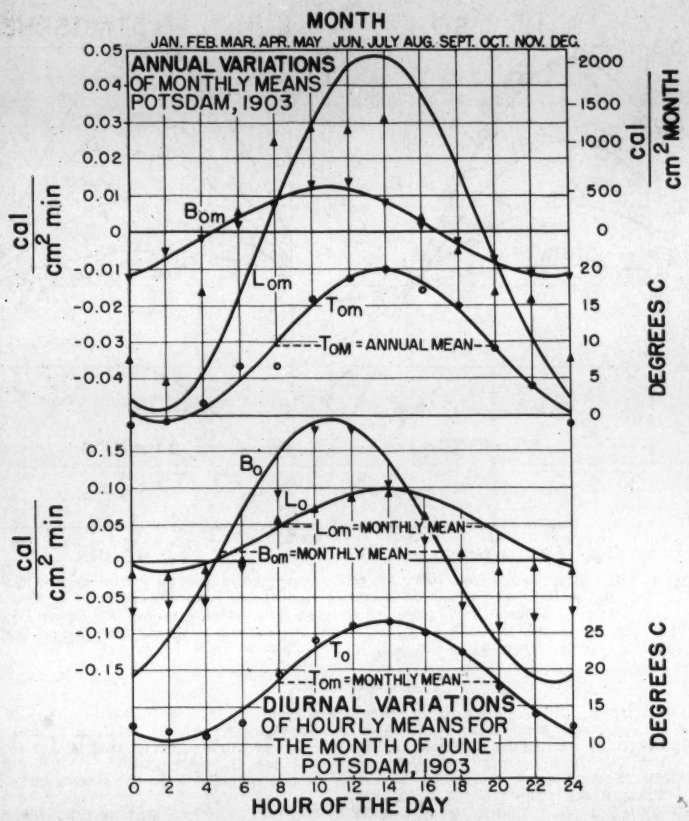


Fig. 2--An example of observed annual and diurnal variations of surface temperature (T_0) and heat transfer from the surface into the soil (B_0) and air (L_0) at the Potsdam Observatory; ○, ▼, and ▲ denote experimental T_0, B_0, and L_0 data which resulted from ALBRECHT'S [1940] analysis; the full lines are theoretical sine waves; the additional subscript m denotes monthly means, M annual means of the 24-hourly averages of T_0, B_0, and L_0. Note that $B_{0M} = 0$ and $L_{0M} = 0$.

variations rather than for monthly means of the diurnal variations or the oscillations on individual days. In the latter case, B_{00} and L_{00} terms must be taken into account as a result of the annual or interdiurnal variations. As an example we refer to Figure 2. The annual course of B_0 and L_0 follows from the monthly means of these terms. Consequently, for the selected month of June, the mean diurnal B_0 and L_0 curves are symmetrical with the monthly means B_{0m} and L_{0m} and not with the zero line whereupon we have $L_{00} = L_{0m}$ and $B_{00} = B_{0m}$ owing to the seasonal variation of duration of daily heat gain versus loss periods in temperate latitudes.

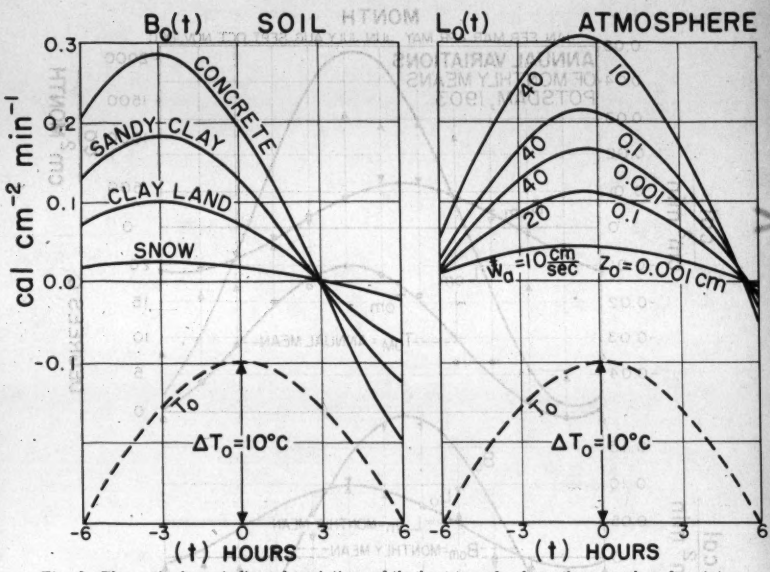


Fig. 3--Theoretical semi-diurnal variations of the heat transfer from the ground surface into the soil (B_0) and atmosphere (L_0) for an arbitrarily assumed surface temperature amplitude (ΔT_0) of 10 C° and indicated soil types and atmospheric conditions; for dry soil (concrete) this chart can be used to compute ΔT_0 for defined atmospheric conditions and given net heat effect of radiative processes $S_0 = B_0 + L_0$; see examples in text.

References

ALBRECHT, F., Untersuchungen ueber den Waermehaushalt der Erdoberflaeche in verschiedenen Klimagebieten, Reichsamt f. Wetterdienst, Berlin, Wissenschaftl. Abh., v. 8, no. 2, 1940.

GEIGER, R., Das Klima der Bodennahen Luftschicht, 2. Aufl., Braunschweig, 1942; American edition, The climate near the ground, Harvard Univ. Press, Cambridge, 1950.

HAURWITZ, B., The daily temperature period for a linear variation of the Austausch coefficient, Trans. R. Soc. Canada, Sec. 3, v. 30, 1936.

INGERSOLL, L., O. J. ZOBEL, and A. C. INGERSOLL, Heat conduction, McGraw-Hill, 1948.

JAHNKE, E., and F. EMDE, Funktionentafeln, 3. Aufl., Leipzig, 1938.

LETTAU, H., Isotropic and non-isotropic turbulence in the atmospheric surface layer, Geophys. Research Papers, no. 1, Air Force Cambridge Res. Lab., Cambridge, Mass., 1949.

PASQUILL, F., Eddy diffusion of water vapour and heat near the ground, Proc. R. Soc., ser. A, v. 198, no. 1052, 1949.

SCHMIDT, W., Wirkungen des Luftaustausches auf das Klima und den taeglichen Gang der Lufttemperatur in der Hoehe, SitzBer., Akad., Wien, Math. Naturw. Kl., v. 127, pt. 2, 1918.

SVERDRUP, H. U., Oceanography for meteorologists, Prentice-Hall, New York, 1942.

Air Force Cambridge Research Laboratories,
230 Albany Street,
Cambridge 39, Massachusetts

(Communicated manuscript received November 22, 1950; open for formal discussion until September 1, 1951.)

Transactions, American Geophysical Union Volume 32, Number 2 April 1951

THE EFFECT OF WAVE STEEPNESS ON WAVE VELOCITY

J. R. Morison

Abstract--Theoretical equations are presented for the effect of wave steepness on wave velocity. Experimental data are presented to show that for practical purposes this effect can be neglected.

Introduction--The theory of oscillatory waves in water of finite depth has been investigated by STOKES [1847] and STRUIK [1926]. These investigations showed that when the wave height is small compared to the wave length or the depth of the water, the wave velocity is given by the following equation

$$C^2 = (gL/2\pi) \tanh (2\pi d/L) \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where C = wave velocity
L = wave length
d = water depth
g = acceleration of gravity

When the wave height H is not small compared to the wave length, (1) no longer applies. STOKES [1847] developed, for this condition, making use of the function H/L (called the wave steepness), a series approximation for the wave velocity. STRUIK [1926] proved the convergence of the series and developed an equation to the third approximation. There was an error, however, in Struik's development, which was corrected by WOLF [1944], and the series was carried out to another term in the approximation. The resulting equation by WOLF [1944] is

$$C^2 = (gL/2\pi)(D_1/S_1)\left\{1 + \mu^2 [(S_2^2 + 2S_2 + 10)/D_1^2] + \mu^4 [(42S_2^5 + 162S_2^4 - 139S_2^3 - 694S_2^2 - 708S_2 - 1408)/12D_1^6]\right\} \quad \ldots\ldots\ldots\ldots (2)$$

where

$$D_n = e^{n2\pi q/CL} - e^{-n2\pi q/CL} = 2 \sinh (n2\pi q/CL) \quad \ldots\ldots\ldots\ldots\ldots (3)$$

$$S_n = e^{n2\pi q/CL} + e^{-n2\pi q/CL} = 2 \cosh (n2\pi q/CL) \quad \ldots\ldots\ldots\ldots\ldots (4)$$

$$\mu = (\pi H/LD_1) - (\pi H/LD_1)^3 (3S_2^3 + 9S_2^2 + 6S_2 - 10)/2D_1^4 \quad \ldots\ldots\ldots (5)$$

and to evaluate q in the above

$$d = (q/C) + (L\mu^2 D_2/4\pi) + (L\mu^4 D_2/4\pi)(S_2^3 + 4S_2^2 + 5S_2)/D_1^4 \quad \ldots\ldots (6)$$

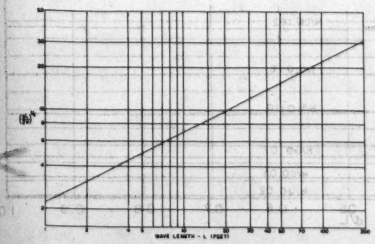


Fig. 1--Wave length (L) versus $(gL/2\pi)^{1/2}$

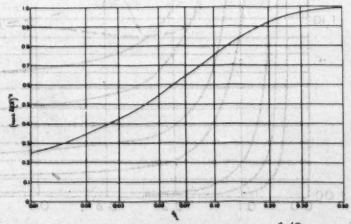


Fig. 2--d/L versus $(\tanh 2\pi d/L)^{1/2}$

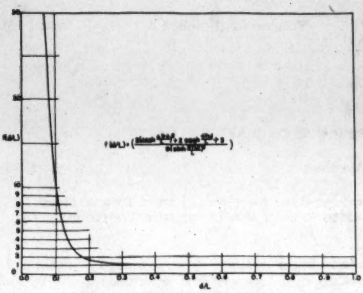


Fig. 3--f(d/L) versus d/L

Eq. (2) to (6) interrelate the variables C, L, d, and H through the parameters μ and q in such a manner that one equation involving only C, L, d, and H cannot be established conveniently. The solution of these equations with three of the variables known is then one of trial and error to determine the fourth varialbe. If H/L is small, then

$$\mu \cong \pi H/LD_1$$

and

$$d \cong q/C$$

Neglecting the third term, (2) reduces to

$$C^2 = [(gL/2\pi)\tanh(2\pi d/L)]\left\{1 + (\pi H/L)^2\,[2\cosh^2(4\pi d/L) + 2\cosh(4\pi d/L) + 5]/8\sinh^4(2\pi d/L)\right\} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (7)$$

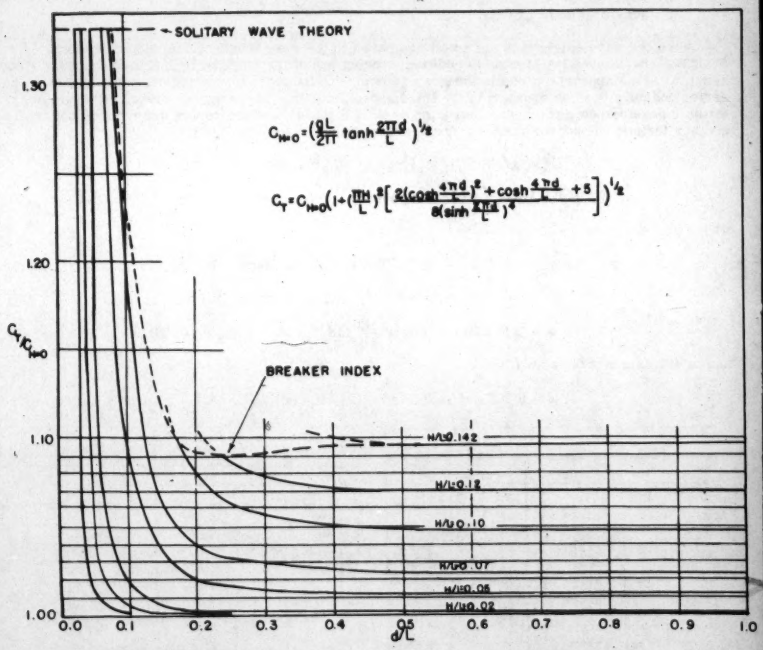


Fig. 4--$C_T/C_{H=0}$ versus d/L for various values of H/L

Table 1--Measured data and computed results on effect of wave steepness on wave velocity

Measured quantities					Computed quantities				
Run	d	T	H	C	C_T	$(C - C_T) \times 100/C$	L	d/L	H/L
	ft	sec	ft	ft/sec	ft/sec	pct	ft		
2	2.00	0.514	0.076	2.89	2.80	+ 3.1	1.49	1.342	0.051
4	2.00	0.507	0.142	2.94	2.89	+ 1.7	1.49	1.342	0.095
3	2.00	0.517	0.124	2.95	2.89	+ 2.0	1.53	1.307	0.081
7	2.00	0.597	0.118	3.32	3.24	+ 2.4	1.98	1.010	0.060
8	2.00	0.597	0.167	3.41	3.34	+ 2.1	2.04	0.980	0.082
9	2.00	0.597	0.205	3.52	3.41	+ 2.3	2.10	0.952	0.098
12	2.00	0.671	0.162	3.77	3.68	+ 2.4	2.53	0.791	0.064
176	1.00	0.533	0.115	2.40	2.66	-10.8	1.28	0.781	0.090
14	2.00	0.693	0.243	3.77	3.82	- 1.3	2.61	0.766	0.093
13	2.00	0.677	0.207	4.09	3.87	+ 5.4	2.77	0.722	0.075
15	2.00	0.682	0.297	4.27	4.06	+ 4.9	2.91	0.687	0.102
225	2.00	0.867	0.362	4.39	4.59	+ 4.6	3.76	0.531	0.096
186	1.00	0.593	0.208	3.37	3.36	+ 0.3	1.99	0.502	0.105
127	2.03	0.858	0.436	4.74	4.81	- 1.5	4.06	0.500	0.108
20	2.00	0.863	0.276	4.64	4.63	+ 0.2	4.01	0.499	0.069
21	2.00	0.867	0.324	4.62	4.67	- 1.1	4.01	0.499	0.081
19	2.00	0.852	0.231	4.79	4.64	+ 3.1	4.08	0.490	0.057
22	2.00	0.876	0.381	4.76	4.79	- 0.6	4.13	0.484	0.092
30	2.00	0.970	0.464	4.52	4.99	-10.4	4.38	0.457	0.106
23	2.00	0.863	0.412	5.11	4.95	+ 3.1	4.41	0.454	0.093
128	2.03	0.916	0.477	5.00	5.09	- 1.8	4.59	0.443	0.104
219	0.91	0.678	0.037	3.23	3.34	- 3.4	2.19	0.413	0.017
27	2.00	0.958	0.271	5.23	5.11	+ 2.3	5.01	0.399	0.054
187	1.00	0.734	0.224	3.60	3.78	- 5.0	2.64	0.379	0.085
69	1.02	0.717	0.256	3.82	3.88	- 1.6	2.73	0.374	0.094
28	2.00	0.958	0.330	5.70	5.34	+ 6.3	5.46	0.366	0.060
29	2.00	0.967	0.405	5.70	5.41	+ 5.1	5.51	0.363	0.074
129	2.03	0.050	0.448	5.45	5.53	- 1.5	5.72	0.355	0.078
39	2.00	1.133	0.496	5.03	5.55	-10.3	5.70	0.351	0.087
36	2.00	1.137	0.372	5.45	5.65	- 3.7	6.20	0.323	0.060
35	2.00	1.140	0.318	5.56	5.68	- 2.2	6.34	0.315	0.050
37	2.00	1.133	0.423	6.04	5.90	+ 2.3	6.84	0.292	0.062
38	2.00	1.133	0.468	6.29	6.02	+ 4.3	7.13	0.281	0.066
131	2.03	1.300	0.455	5.74	6.12	+ 6.6	7.45	0.273	0.061
171	1.98	1.288	0.434	5.74	6.08	- 5.9	7.40	0.268	0.059
122	1.99	1.300	0.360	5.77	6.07	- 5.2	7.50	0.265	0.048
211	2.00	1.420	0.353	5.63	6.21	-10.3	7.99	0.250	0.044
212	2.00	1.437	0.393	5.63	6.26	-11.2	8.09	0.247	0.049
64	1.01	0.966	0.342	4.45	4.65	- 4.5	4.30	0.235	0.080
67	1.01	0.966	0.349	4.48	4.67	- 4.2	4.33	0.233	0.081
66	1.01	0.966	0.342	4.50	4.67	- 3.8	4.35	0.232	0.079
65	1.01	0.975	0.349	4.50	4.70	- 4.4	4.38	0.231	0.080
213	2.00	1.437	0.465	6.08	6.46	- 6.3	8.74	0.229	0.053
132	2.03	1.340	0.436	6.80	6.54	+ 3.8	9.10	0.223	0.048
172	1.96	1.375	0.363	6.55	6.45	+ 1.5	9.01	0.218	0.040
75	1.02	1.000	0.242	4.68	4.69	- 0.2	4.68	0.216	0.052
76	1.02	1.030	0.240	4.61	4.71	- 2.2	4.74	0.213	0.051
124	1.99	1.460	0.346	6.43	6.54	- 1.7	9.38	0.212	0.037
189	1.00	1.040	0.240	4.56	4.69	- 2.9	4.74	0.212	0.051
55	1.02	1.180	0.363	4.76	5.05	- 6.1	5.62	0.181	0.065
190	1.00	1.220	0.228	4.56	4.90	- 7.5	5.56	0.180	0.041
135	2.03	1.720	0.475	6.55	6.98	- 6.6	11.30	0.179	0.042
51	1.02	1.160	0.355	4.94	5.08	- 2.8	5.72	0.178	0.062
82	1.01	1.200	0.233	5.04	5.01	+ 0.6	6.05	0.167	0.039
191	1.00	1.380	0.237	4.68	5.08	- 8.6	6.45	0.155	0.037
217	0.58	0.930	0.317	4.15	4.19	- 1.0	3.86	0.151	0.082
56	1.01	1.350	0.378	5.04	5.30	- 5.2	6.80	0.149	0.056
58	1.01	1.330	0.378	5.16	5.31	- 2.9	6.87	0.147	0.055
59	1.01	1.330	0.377	5.11	5.31	- 3.9	6.89	0.147	0.055

(continued)

Table 1--Measured data and computed results on effect of wave steepness on wave velocity (concluded)

Run	Measured quantities				Computed quantities				
	d	T	H	C	C_T	$(C - C_T) \times 100/C$	L	d/L	H/L
	ft	sec	ft	ft/sec	ft/sec	pct	ft		
109	0.78	1.180	0.310	4.66	4.73	- 1.5	5.52	0.141	0.056
110	0.78	1.215	0.315	4.61	4.75	- 3.0	5.60	0.139	0.056
224	0.49	0.983	0.038	3.79	3.61	+ 4.8	3.67	0.134	0.010
107	0.88	1.380	0.380	5.00	5.10	- 3.6	6.90	0.127	0.055
61	1.01	1.600	0.390	5.26	5.56	- 5.7	8.42	0.120	0.046
60	1.01	1.550	0.395	5.54	5.56	- 0.7	8.60	0.117	0.046
221	0.91	1.733	0.093	5.45	5.14	+ 5.7	9.45	0.096	0.010

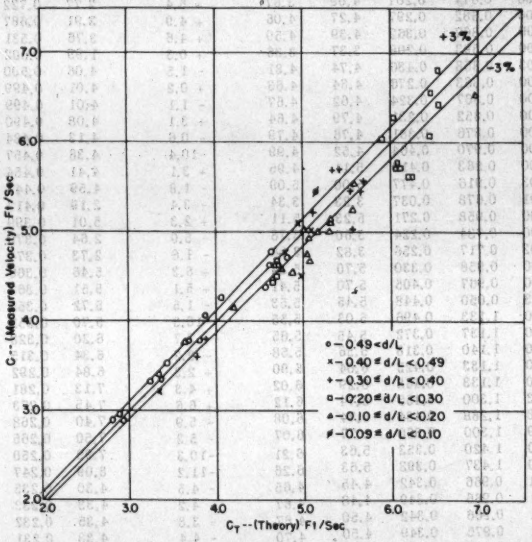


Fig. 5--Measured velocity versus theoretical velocity

Eq. (7) is the corrected form of Struik's equation. When H/L becomes small, the above equation, of course, reduces to (1). If the wave velocity as given by (1) is designated by the symbol $C_{H=0}$ and that by (7) by C_T, the ratio of the two velocities is given by the expression

$$C_T/C_{H=0} = \left\{1 + (\pi H/L)^2\ [f(d/L)]\right\}^{1/2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

and shows the effect of wave steepness (H/L) on the wave velocity. In (8)

$$f(d/L) = [2\cosh^2(4\pi d/L) + 2\cosh(4\pi d/L) + 5]/8\sinh^4(2\pi d/L)$$

It was this part of Struik's equation that was modified by Wolf so that for large values of d/L or "deep water" conditions the value of f(d/L) = 1.

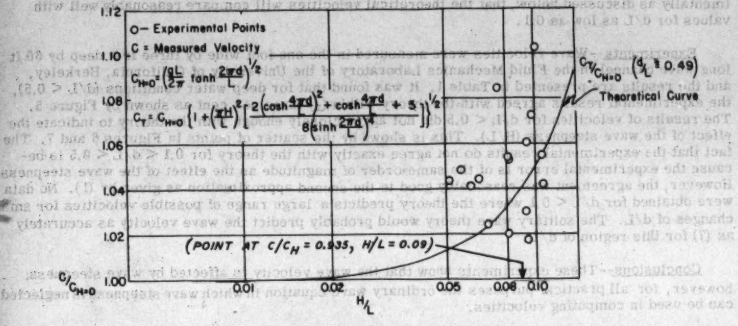


Fig. 6--Wave steepness effect in deep water

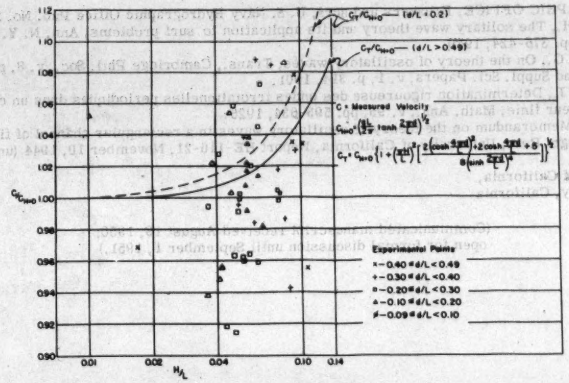


Fig. 7--Wave steepness effect in shallow water

As illustrated by Figures 1 to 4, it is convenient when making calculations by the above equations to have plots of $\sqrt{gL/2\pi}$ against L, $\sqrt{\tanh(2\pi d/L)}$ against d/L, $f(d/L)$ against d/L, and $C_T/C_{H=0}$ against d/L with H/L as a parameter. The values of Figures 1 and 2 multiplied together give (1), $C_{H=0}$. Figure 3 shows that $f(d/L)$ becomes large for d/L values less than 0.1 or for very shallow water. These factors combined with the wave steepness (H/L) are shown in Figure 4 where the breaker index and solitary wave theory form the empirical and theoretical boundaries for the possible values of velocities. The breaker index gives the maximum wave steepness possible for any d/L ratio and was empirically determined [HYDROGRAPHIC OFFICE, 1944]. The solitary wave velocity is the maximum velocity for a wave of finite amplitude in very shallow water and was theoretically determined by MUNK [1949]. It should be noted that the theory for very shallow water ($d/L < 0.1$) predicts a large range of values of $C_T/C_{H=0}$ for a small range of d/L. This indicates that the velocities determined for low values of d/L probably will show large scatter when compared to experimental measurements. Experimental results show that for the lower values of d/L ($d/L < 0.5$) considerable scatter is present; however, no values of velocity have been obtained for $d/L < 0.1$. It should be remembered that the theoretical wave velocity was for "deep water" conditions; however, from Figure 4 it is reasonable to expect, and it has been found exper-

imentally as discussed below, that the theoretical velocities will compare reasonably well with values for d/L as low as 0.1.

Experiments--Wave velocities were measured in the one foot wide by three feet deep by 60 ft long wave channel in the Fluid Mechanics Laboratory of the University of California, Berkeley, and the results are presented in Table 1. It was found that for deep water conditions ($d/L \leq 0.5$), the experimental results agreed with the theory within ($\pm$) three per cent as shown by Figure 5. The results of velocities for $d/L < 0.5$ did not agree closely enough with the theory to indicate the effect of the wave steepness (H/L). This is shown by the scatter of points in Figures 6 and 7. The fact that the experimental results do not agree exactly with the theory for $0.1 < d/L < 0.5$ is because the experimental error is of the same order of magnitude as the effect of the wave steepness. However, the agreement was reasonably good to the second approximation as given by (1). No data were obtained for $d/L < 0.1$ where the theory predicts a large range of possible velocities for small changes of d/L. The solitary wave theory would probably predict the wave velocity as accurately as (7) for this region of d/L.

Conclusions--These experiments show that the wave velocity is affected by wave steepness; however, for all practical purposes the ordinary wave equation in which wave steepness is neglected can be used in computing velocities.

References

HYDROGRAPHIC OFFICE, Breakers and surf, U. S. Navy Hydrographic Office Pub. No. 234, 1944.

MUNK, W. H., The solitary wave theory and its application to surf problems, Ann. N. Y. Acad. Sci., v. 51, pp. 376-424, 1949.

STOKES, G. G., On the theory of oscillatory waves, Trans., Cambridge Phil. Soc., v. 8, p. 441, 1847, and Suppl. Sci. Papers, v. 1, p. 314, 1901.

STRUIK, D. J., Détermination rigoureuse des ondes irrotationelles periodiques dans un canal à profondeur finie, Math. Ann., v. 95, pp. 595-634, 1926.

WOLF, F., Memorandum on the theory of oscillatory waves in a rectangular channel of finite depth, Inst. Engr. Res., University of California, Report HE-116-21, November 10, 1944 (unpublished).

University of California,
Berkeley, California

(Communicated manuscript received August 19, 1950;
open for formal discussion until September 1, 1951.)

Transactions, American Geophysical Union Volume 32, Number 2 April 1951

SOME OBSERVATIONS OF THE VELOCITY PROFILE NEAR THE SEA FLOOR

R. M. Lesser

Abstract--Observations of the current speed at four levels near the sea floor in shallow water show that the velocity profile follows a logarithmic curve. Conditions of rough and smooth turbulence are found to exist.

Introduction--The velocity profile near the sea floor is of interest to physical oceanographers in the study of boundary processes and to submarine geologists in the study of sediment transport. Comparatively few measurements have been made up to the present time, so little information is available on this subject.

The turbulence theories of von Karman and Prandtl have been used as the basis for the attempt at a quantitative explanation of flow near the sea floor. No attempt is made to modify the theory. Observed values are substituted directly into the equations.

Instrumentation--In order to obtain sufficient data to carry through any hydrodynamic study of flow near the sea floor, it is necessary to measure current speeds at several heights near the bottom, obtaining a quantitative measure of the velocity distribution with height in the turbulent layer. The currents near the bottom in this study were measured with four Ekman-type current meters mounted on a tripod. The meters were arranged so that when the tripod was lowered to the bottom, measurements of current speed and direction could be made at 20, 40, 80, and 160 cm above the sea floor (see Fig. 1). The equipment was designed so that the four meters were tripped simultaneously by the slackening of the lowering line when the tripod reached the bottom. Resumption of tension on the line arrested the operation of the meters and prevented them from registering while being retrieved. The measurements were made from an anchored ship in water of about 25-fm depth. This depth was below that of wave action in the area where the measurements were made.

Samples of the sea floor sediment were taken in conjunction with each current observation in order to obtain an idea of the character of the bottom. A total of 18 observations was made over three types of sea floor: mud, mud-sand, and gravel-sand.

Theory--The Prandtl equation for turbulent flow over a rough boundary surface (hereafter called rough turbulence) is

$$\tau = (\rho k_0^2 v^2)/[\log_e (z + z_0)/z_0]^2 \quad \text{or} \quad v = (v'/k_0) \log_e [(z + z_0)/z_0] \quad \ldots\ldots\ldots (1)$$

where τ is the frictional stress; ρ is the density of the fluid; v' is the roughness velocity, $\sqrt{\tau/\rho}$; z_0 is the roughness parameter; k_0 is von Karman's constant; and v is the speed at the height z above the boundary. With k_0 equal to 0.40 and introducing base-10 logarithms, one arrives at

$$\tau = 0.0302\ \rho v^2/[\log_{10} (z + z_0)/z_0]^2 \quad \text{or} \quad v = 5.75\ v' \log_{10} [(z + z_0)/z_0] \ldots\ldots\ldots (2)$$

The roughness parameter, z_0, may be determined from

$$\log_e z_0 = (v_1 \log_e z_2 - v_2 \log_e z_1)/(v_1 - v_2) \ldots\ldots\ldots\ldots\ldots (3)$$

where v_1 and v_2 are the speeds at the heights z_1 and z_2.

The above equations are not applicable to a smooth boundary surface. The von Karman equation for turbulent flow over a smooth boundary surface (hereafter called smooth turbulence) is

$$v/v' = 5.5 + (1/k_0) \log_e v' z/\nu \ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

where ν is the kinematic viscosity of the fluid. With k_0 equal to 0.40 and introducing base-10 logarithms, one obtains

$$v/v' = 5.5 + 5.75 \log_{10} v' z/\nu \ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

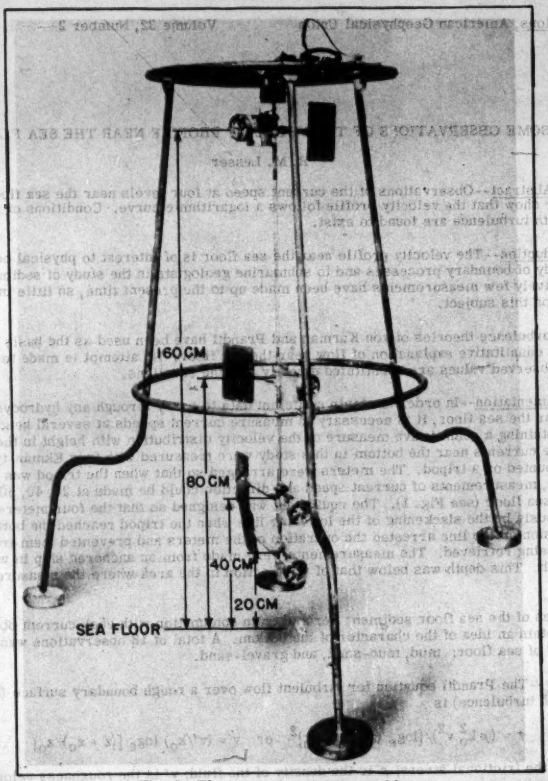


Fig. 1--The current meter assembly

Analysis and results--Both theory and laboratory experiments show that the velocity near the boundary increases logarithmically with height in the turbulent region. In order to verify this in the oceans, it is necessary to measure current speed in the turbulent region at three or more levels above the sea floor. Four levels were used in this particular study. Density of the water was determined by temperature and salinity measurements, and the water was found to be nearly homogeneous in the turbulent region, with an average density of 1.025 g/cm^3.

The speed-height relationship was plotted on semi-logarithmic paper, with speed on the linear scale and height on the logarithmic. The plots (see Fig. 2) show that the velocity distribution followed a logarithmic relationship. The direction of flow did not change appreciably with height above the bottom.

The values of the velocity used in this study are horizontal velocity components, since no instrumentation has as yet been developed for the measurement of vertical velocity components in the sea. It is probable, however, that the vector change from the horizontal component is smaller than any amount measurable by the instruments. The accuracy of measurement is such that the vertical component can be neglected.

Table 1--Calculations of frictional stress and roughness velocity

Sea floor	e	z_o	Average velocity	Height above sea floor	v'_R	v'_S	τ_R	τ_S
	mm	mm	cm/sec	cm	cm/sec	cm/sec	gm/cm/sec^2	gm/cm/sec^2
Gravel-sand	2.0	1.3	22.6	160	1.27	0.81	1.66	0.64
Gravel-sand	2.0	1.3	20.3	80	1.26	0.78	1.64	0.59
Gravel-sand	2.0	1.3	18.2	40	1.27	0.75	1.65	0.55
Gravel-sand	2.0	1.3	15.9	20	1.26	0.71	1.63	0.49
Mud-sand	1.5	1.6	39.7	160	2.30	1.36	5.42	1.80
Mud-sand	1.5	1.6	35.8	80	2.31	1.31	5.44	1.68
Mud-sand	1.5	1.6	31.6	40	2.29	1.25	5.37	1.52
Mud-sand	1.5	1.6	27.7	20	2.29	1.18	5.38	1.36
Mud	0.05	0.2	12.7	160	0.57	0.48	0.33	0.22
Mud	0.05	0.2	11.6	80	0.56	0.47	0.32	0.21
Mud	0.05	0.2	10.8	40	0.57	0.47	0.33	0.21
Mud	0.05	0.2	9.7	20	0.56	0.46	0.32	0.21

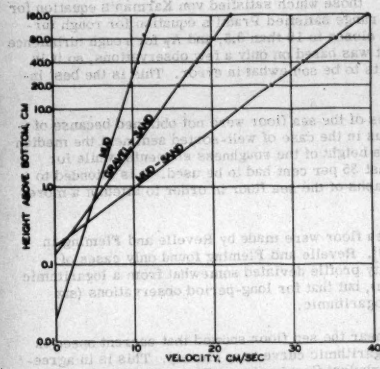


Fig. 2--Speed-height relationships for three types of bottom

The equation of the line of best fit connecting the four points was determined statistically for each observation by the method of least squares modified for use on a logarithmic function [RIDER, 1939]. The observed velocities at all four points fell close to the line of best fit. In about half the cases the speeds followed the line within the limits of accuracy of the observations, and the average deviation of speed was three per cent, with a maximum for one observation of ten per cent.

The roughness parameter, z_o, was determined from (3). Values of z_o are presented along with the calculations of stress, roughness velocity, and the diameter of the roughness elements, e, in Table 1.

The roughness velocity, v', was determined from (2) and (5) for rough and smooth turbulence, respectively. It was found that the relationship for rough turbulence held over mud-sand and gravel-sand sea floors. For mud bottom, the relationship for smooth turbulence appeared to hold.

A mechanical analysis of the sediment was performed by A. J. Carsola of this laboratory. The analysis showed the mud-sand and gravel-sand to be poorly sorted, with median diameters of 0.54 and 0.88 mm, respectively. Average roughness parameters for these were 1.6 and 1.3 mm, respectively. This anomalous situation cannot be explained except that ripple marks or other unknown irregularities may have been present in either or both cases. Also, more than 35 per cent of the sediment had diameters of greater than 2.0 mm, and it is possible that the bottom roughness is due to this sediment of larger diameter. The mud sediment was well sorted, with a median diameter of 0.05 mm and, if considered as a rough surface, a roughness parameter of 0.2 mm.

Experiments by NIKURADSE [1933] indicate that a criterion for determining the type of boundary is a critical value of a dimensionless Reynolds number, $E = v'e/\nu$, where e is the height of the roughness elements and v' is the roughness velocity. WHITE [1940] found that for a rough boundary, E is greater than 3.5 and for a smooth boundary, E is less than 3.5.

Application of White's criterion for boundary conditions gives a value of E greater than 3.5 for all observations. However, this value is questionable for the sea floor. White determined his value experimentally in the laboratory, using a flat surface with homogeneous roughness elements.

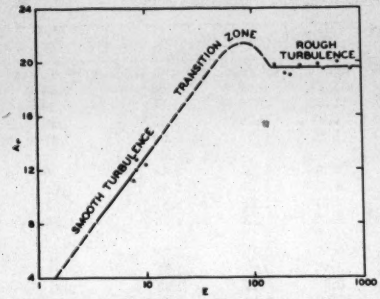


Fig. 3--Relationship between turbulence and Reynolds number for the sea floor

Natural sediments are almost never homogeneous. In addition, White's criterion did not take into account any irregularities in sea floor topography, such as ripple marks.

An attempt was made to reproduce Nikuradse's curve for turbulent flow in pipes. For rough turbulence, Nikuradse found a constant value of 8.48 for the dimensionless quantity $A_r = mE - (1/k_0) \log_e m$, where m is the ratio between the thickness of the laminar film and the height of the roughness elements, and E is the roughness Reynolds number. Figure 3 shows the relationship between turbulence and roughness Reynolds number for the sea floor. The curve for the sea floor was drawn through the observed values to approximate the shape of Nikuradse's curve for turbulent flow in pipes. Points were found in the rough zone and in the smooth, but none in the transition between rough and smooth. The points in the smooth zone were those which satisfied von Karman's equation for smooth turbulence, while the points in the rough range satisfied Prandtl's equation for rough turbulence. The critical value of E was found to be closer to 10 than 3.5, and A_r for rough turbulence turned out to be 19.5 instead of 8.48. This result was based on only a few observations, so it is possible that further study may show these results to be somewhat in error. This is the best information available to date, however.

Also, photographs to determine irregularities of the sea floor were not obtained because of the general turbid character of the water, and thus in the case of well-sorted sediment the median diameter of the sediment had to be used for e, the height of the roughness elements, while for poorly-sorted sediment the diameter of the largest 35 per cent had to be used. It is intended to collect more data in the near future with photographs of the sea floor in order to attempt a more conclusive result.

Previous measurements of currents at the sea floor were made by Revelle and Fleming in 1937 (unpublished), and by MOSBY [1947 and 1949]. Revelle and Fleming found only cases of rough turbulence, and Mosby found that the velocity profile deviated somewhat from a logarithmic curve for short-period observations (up to 25 min), but that for long-period observations (six hours) the velocity distribution was very nearly logarithmic.

Conclusions--A study of the velocity profile near the sea floor showed that current speed in the turbulent region near the bottom followed a logarithmic curve very closely. This is in agreement with the Prandtl-von Karman theories for turbulent flow in pipes. The value of the roughness Reynolds number for the transition from smooth to rough turbulence appeared to be higher at the sea floor than that found by Nikuradse for flow in pipes.

In most cases, rough turbulence was observed to exist near the sea floor, but evidence of the existence of smooth turbulence was found. It should be recalled, however, that the sea floor at a given location may possibly act as either a smooth or a rough surface, depending upon the speed of flow and the velocity gradient.

Acknowledgments--The writer desires to thank the members of the Oceanography Section, U. S. Navy Electronics Laboratory, for their help in collecting the data which made this study possible; A. J. Carsola for his analysis of the sediment samples; and G. L. Prible for his help in the preparation of the figures. The writer also wishes to thank E. C. La Fond, R. R. Revelle, J. F. T. Saur, Jr., D. L. Inman, D. W. Pritchard, and R. O. Reid, for their helpful suggestions and critical reading of the manuscript.

References

MOSBY, H., Experiments on turbulence and friction near the bottom of the sea, Bergens Mus. Årbok, Naturvitensk. rekke, no. 3, 6 pp., 1947.

MOSBY, H., Experiments on bottom friction, Bergens Mus. Årbok 1949-1950, Naturvitensk. rekke, no. 10, pp. 3-12, 1949.

NIKURADSE, J., Stromungsgesetze in rauhen Rohren, Ver. Deutsch. Ing., Forschungsheft 361, 1933.
RIDER, P. R., An introduction to modern statistical methods, John Wiley, 1939.
WHITE, C. M., The equilibrium of grains on the bed of a stream, Proc. R. Soc., Ser. A, v. 174, pp. 322-338, 1940.

U. S. Navy Electronics Laboratory,
San Diego, California

(Communicated manuscript received November 29, 1950;
open for formal discussion until September 1, 1951.)

ACTIVITY OF PARICUTIN VOLCANO FROM JANUARY 1 TO JUNE 30, 1950

Carl Fries, Jr. and Celedonio Gutiérrez

(Published by permission of the Director, U. S. Geological Survey)

The activity of Parícutin Volcano during the first half of 1950 is here described in much the same form that was used in the report for the second half of 1949 [FRIES and GUTIERREZ, 1950]. The diagrams showing eruptive characteristics (see Fig. 1-3) carry a new letter (P) for a noise type not formerly recognized or reported as such, but that is sufficiently distinct and frequent to warrant noting separately. This and the rest of the lettered noise types used are described in Table 1, so that the reader may refer to them conveniently without referring to earlier publications.

The junior author, assisted by Jesús Saldaña, made the daily observations that form the basis for the eruptive diagrams and for the summary of weather, rainfall, and ashfall given in Table 2. They also determined the monthly advance of the new lava, shown in Figure 5, and kept a brief written daily record of significant or out-of-the-ordinary events. All these data, together with personal observations of the senior author in the periods February 19-22, April 26-29, and July 6-9, were evaluated and compiled in preparing the present report. The photographs that appear in Figures 4, 6, and 7, the elevations of points on the cone given in Table 4, the calculations of lava volume, and comparisons with activity in former years were contributed also by the senior author.

Eruptive activity--Eruptions from the crater continued to be as erratic as in other years, as illustrated in detail in the accompanying diagrams (see Fig. 1-3). In general, however, the months of January and February were characterized by frequent, tremendously strong explosions (see Fig. 4) that hurled out great quantities of rock fragments and pasty lava, some as large as several tons, which fell at times as far as two kilometers from the eruptive vent. These explosions were generally preceded by several minutes of complete inactivity. They occurred on more than 15 days during these two months and were accompanied by local Earth tremors. March and April were characterized by moderately strong activity and frequent, though somewhat less intense and more heavily charged, eruptions than those of the first two months. During May and June the strong explosions were infrequent and the eruptions consisted largely of whitish to yellowish gases with small quantities of rock fragments and very little ash. Electric discharges within the eruptive column accompanied the stronger eruptions during every month of the period described.

The lettered noise types shown in the eruptive diagrams are described in Table 1. All these types except that indicated by the letter P had formerly been described by WILCOX [1947] and are merely repeated here for convenience. The new type of noise sounds more nearly like type D than like any of the others, but it differs in that the explosions are very short and are repeated rapidly at intervals of one to two seconds. This type of noise was first distinguished in March and was audible from time to time in the following months.

The eruptive column rose to a maximum height of about 4000 m above the top of the cone on February 16, after a particularly strong explosion. On several other days it reached heights of 3000 to 3500 m, but in general it flattened out in the upper winds at a height of less than 2500 m above the cone. Eruption of ash continued to decline gradually. At the more distant Cuezeño Station the total ashfall was only 5.1 mm (see Table 2), and at the closer Equijuata Station it was 7.7 mm during the six-month period. Table 3 shows the constant decrease in ashfall at Cuezeño for the three yearly periods from July 1947 to June 1950, during which precise records have been maintained. The total for this three-year period was only 51.9 mm, whereas in the three years and eight months from February 1943 to October 1946, at least 480 mm of ash fell at Cuezeño [SEGERSTROM, 1950 pl. 1].

Form of the cone and crater--The outer form of the cone remained about the same throughout the first half of 1950. Periodic slumps of the northeast flank in January, February, and April

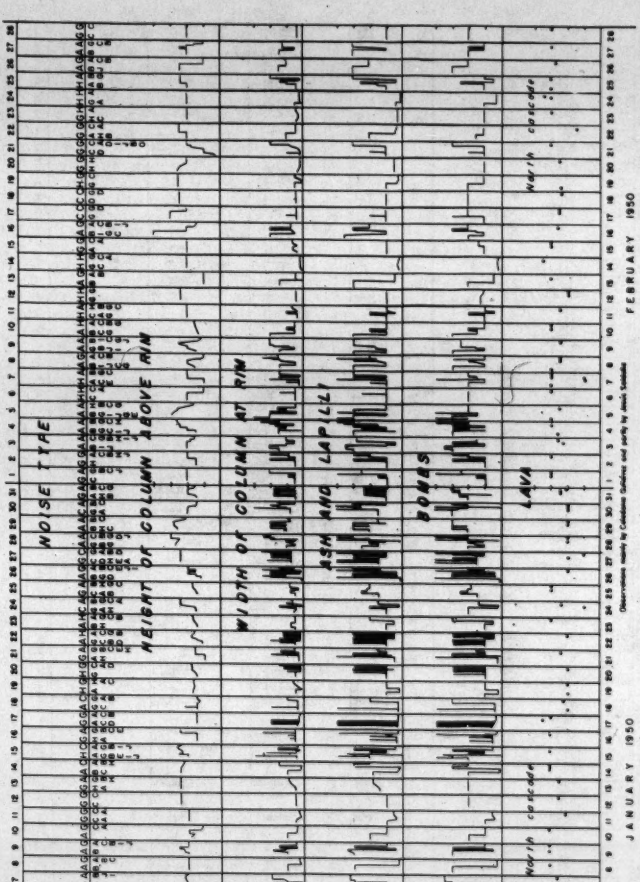


Fig. 1--Eruptive characteristics of Parícutin Volcano from January 1 to February 28, 1950

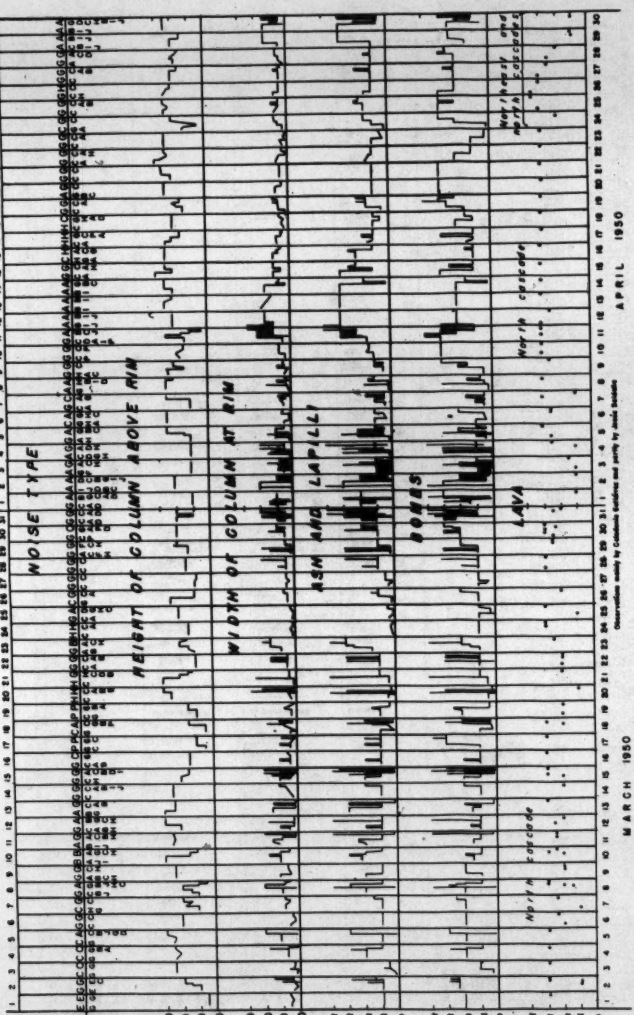


Fig. 2--Eruptive characteristics of Parícutin Volcano from March 1 to April 30, 1950

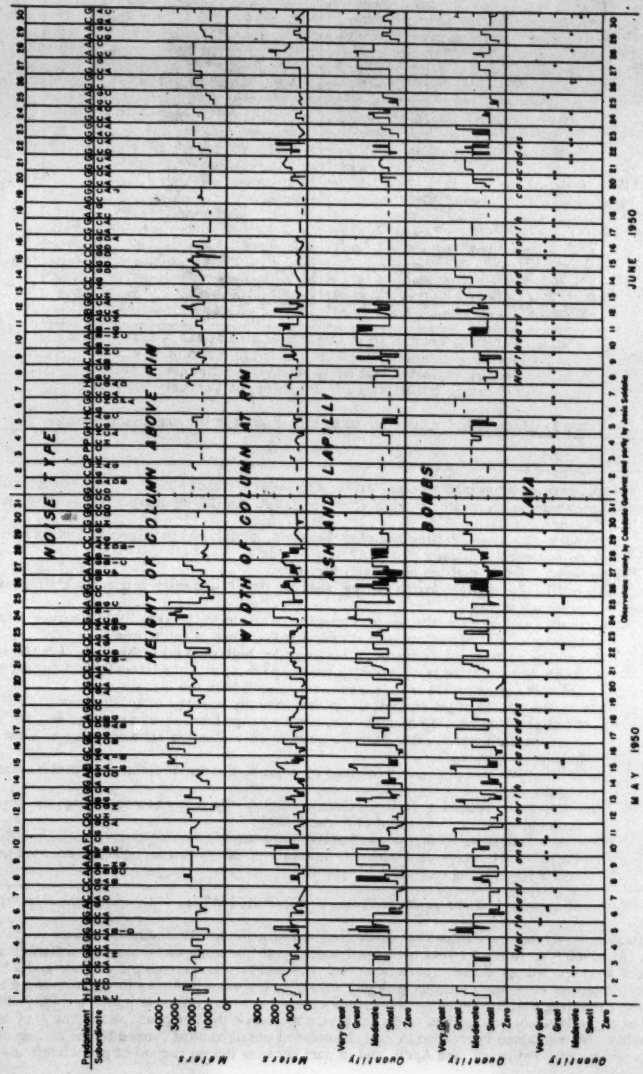


Fig. 3--Eruptive characteristics of Paricutin Volcano from May 1 to June 30, 1950

Fig. 4--Parícutin Volcano from Cuezeño Station at end of four-minute period of complete quiescence (left), followed by an earth-shaking explosion that hurled bombs two kilometers from the crater (right), two minutes later, on February 21, 1950

Table 1--Description of lettered noise types[a] used in the eruptive diagrams

Type	Description
A	Soft surging or swishing noise, barely audible at distances greater than one kilometer
B	Louder and more profound surging noise than A, similar to heavy surf breaking on a shore
C	Thunder-like noise, rolling and reverberating, lasting two to fifteen sec, often initiated by heavier explosions
D	Noise like that of muffled heavy artillery fire
E	Noise like that of light artillery fire, sharper than D and often producing visible compression waves
F	A steady rushing roar like the jet emission of steam under very high pressure, continuing uninterrupted for periods ranging from one to thirty min
G	Undulating noise of jet emission of steam under high pressure; this type of noise sounds much like a distant fast-traveling railroad train, with the intensity and quality of the noise changing as the train passes irregularities in the terrain
H	Intermittent noise of jet emission of steam, usually harsher in quality than that of F or G; alternating periods of noise and silence range from three to 60 sec and are at times sufficiently regular in periodicity to resemble the slow chugging of a hard-pulling freight engine
I	Noise like that of a pistol shot, caused by point discharge of electricity in the eruptive column
J	Flat slap noise caused by falling volcanic bombs; with many bombs falling, the noise resembles the confused beat of horses' hoofs
O	Complete lack of noise for more than five minutes
P	Repeated, short, sharp explosions at intervals of one to two seconds, terminated generally by a strong explosion of type C

[a]Repeated from an earlier published report [WILCOX, 1947, p. 569], except the new type P.

continued to keep that part somewhat depressed and to maintain the northeast saddle in the crater rim. At 08^h00^m on April 2 a vent blew open suddenly at midslope on the northeast flank, and from it were hurled out dense vapors, ash, and rock and lava fragments for an hour and a half. These eruptions were simultaneous with and nearly on the same scale as those from the main crater, indicating that the vents were probably connected within the cone itself, possibly along the top of the lava conduit leading to the lava-vent mound on the northeast side. The southwest flank has also remained depressed in part, because of small slumps caused by the strong explosions of January, February, and April, and in part because the increment of pyroclastic material

Table 2--Monthly summaries of weather observations, rainfall, and ashfall near Parícutin Volcano

Month	Cuezeño station							Average direction of upper winds	Equijuata station	
	Temperature		Rainfall	Ashfall		Min. humidity			Rainfall (total)	Ashfall (total)
	Max.	Min.	Total	Max.	Total	Max.				
1950	°C	°C	mm	mm	mm	mm	pct		mm	mm
January	25.0	2.5	24.0	13.5	1.9	1.0	16	ESE	42.0	1.5
February	27.8	0.0	9.0	5.7	0.4	0.4	12	SSW and NE	10.5	0.5
March	30.3	2.5	28.7	14.2	1.0	0.5	9	SW	74.5	2.0
April	29.4	5.0	0.0	0.0	1.8	0.4	12	SW	0.0	2.1
May	31.1	8.1	61.9	24.0	tr	tr	14	W and NE	105.8	0.7
June	26.7	7.8	302.1	48.0	0.0	0.0	31	ESE	361.5	0.9

Table 3--Rainfall and ashfall at Cuezeño Station for the yearly periods from July 1946 to June 1950[a]

Period	Rainfall (total)	Ashfall (total)
July 1946 to June 1947	1707.0	?
July 1947 to June 1948	1455.0	30.0
July 1948 to June 1949	1584.3	12.2
July 1949 to June 1950	1456.6	9.1

[a]Compiled in part from earlier published reports.

has apparently not been great enough to eradicate the effect of the large slumps of that flank in the last half of 1949.

The elevation of points on the rim of the volcano (see Table 4 and Fig. 5) did not change greatly in the first half of 1950. The northeast saddle is several meters lower because of slumping over the lava conduit, which presumably passes under or through that flank. The outer east peak has risen a meter or so, and the inner east peak has apparently slumped somewhat into the crater, dropping about three meters in height. The profile of the cone, viewed from the north, continues to show three points (see Fig. 4), which correspond to the outer east peak, the inner east peak (east rim of presently active crater), and the west peak. The maximum height of the cone above its original base was about 397 m on February 21, 1950 (see Table 5), in comparison with 360 m on the same day of 1947 and 336 m on that day of 1944 [SEGERSTROM, 1950, p. 28]. Hence, in the three years after the end of the first year of eruptive activity, the cone rose about 24 m, and in the following period of three years it rose 37 m. This suggests that in recent years coarse pyroclastic material erupted from the crater has not decreased as greatly in volume as has the finer ash, confirming visual estimates of those who have observed the activity over the past seven years.

The part of the cone visible is somewhat smaller now than it was three years ago. By way of comparison, the maximum diameter of the base of the cone, from northwest to southeast, was 1100 m in February 1946 [SEGERSTROM, 1950, p. 28] and the minimum diameter was 950 m, whereas the present maximum, in the same direction, is 940 m and the minimum is 700 m. The maximum diameter of the rim in February 1946 was 400 m, whereas it is now only 280 m. The decrease at the base has been caused by the piling up of lava flows over the lower slopes; the decrease at the

Table 4--Elevation[a] above sea level of points on Parícutin Volcano

Date	West peak	Lowest point of northeast rim	Outer east peak[b]	Inner east peak[c]	Lava-vent mound
1950	m	m	m	m	m
February 21	2795.1	2770.8	2772.7	2783.5	2650.8
April 28	2796.6	2770.8	2774.2	2783.5	2655.1
July 7	2796.6	2766.3	2774.2	2780.5	2656.6

[a]Determined by alidade from Cuezeño station; estimated accuracy of ± 1.5 m.
[b]Point recorded in earlier published activity reports.
[c]Point on rim of inner crater; horizontal distance from Cuezeño station is 5240 m.

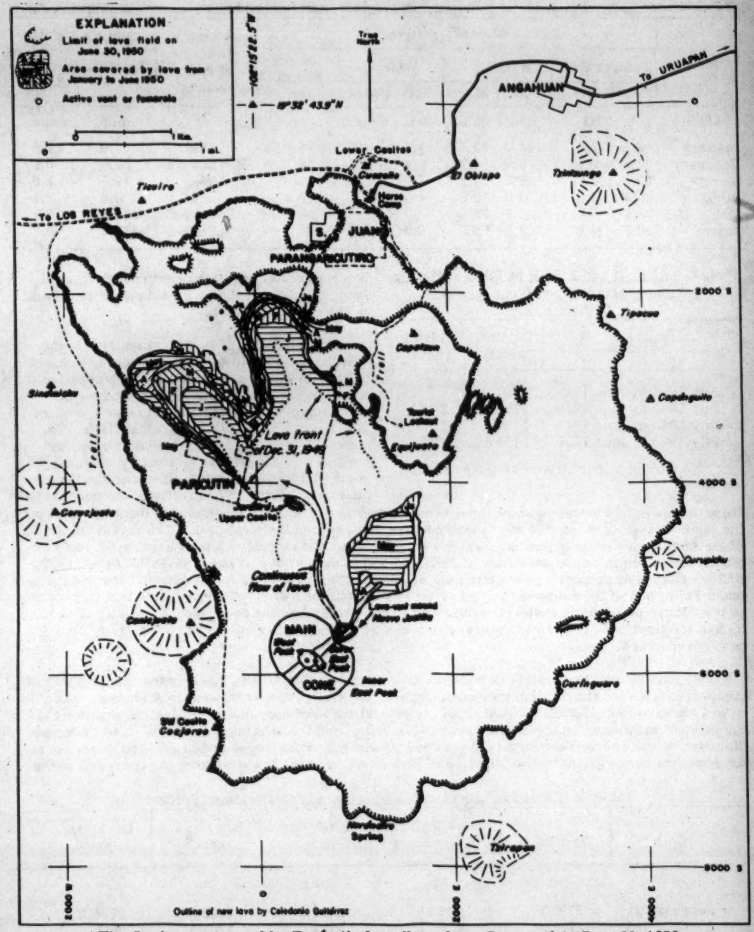


Fig. 5--Areas covered by Parícutin lava flows from January 1 to June 30, 1950

top has been due to a decline in the average intensity of the eruptions, which are now not strong enough to keep such a wide crater cleaned out.

The active part of the crater continued to show variations in depth, form, and the location of eruptive throats. In general, only one throat was active at any one time during most of the period. On several days in early and late June, however, simultaneously active throats were noted independently by the junior author and Howel Williams. On ascents to the crater on April 28 and July

Table 5--Changes in height of Parícutin cone

Date	Height of cone	Increase in height between dates shown		Period of time elapsed	
	m	m	m		
February 23, 1943	44[a]	336	44	3 days	1 yr
June 9, 1943	198		154	3 1/2 mo	
February 20, 1944	336		138	8 1/2 mo	
February 20, 1947	360	61	24	3 yr	6 yr
February 21, 1950	397		37	3 yr	

[a]Figures from a published report [SEGERSTROM, 1950, p. 28].

7, the senior author found the crater to be about 20 or 25 m deep, in the form of a single bowl with an elongated bottom oriented in a northwest-southeast direction. This departure from the normal northeast-southwest elongation of the crater bottom, or alinement of the throats, had never been noted before, and it was apparently constant for several months. Eruptions came from the northwest end of the elongated bottom in April, and from the southeast end in July. At both times the bottom was red-hot and the actual throats were less than three meters across. The throats blew open somewhat plastically with each eruption, but the activity was too strong and erratic to permit spending more than a few minutes on top of the volcano for further observation. This crater seems to occupy the normal southwest eruptive-throat area, and the normal northeast throat area has apparently been completely covered over by pyroclastic material. The rim of the crater is a sharp ridge except around the eastern side, where there is a terrace between the inner and outer east peaks about 80 m in maximum width.

Activity of the lava vents--Lava issued only from the northeast Nuevo Juatita vent during the first half of 1950 and had, by the end of June, been flowing continuously from this vent for two years and five months. The mound around the vent continued to rise as a result of periodic flooding and was about nine meters higher at the end of the period than at the beginning (see Table 4 and Fig. 4). This mound had risen seven meters in the preceding six-month period and about 19 m in the year before that, making a total rise of 35 m in two years. At the end of June 1950, the vent mound was only 110 m below the northeast saddle of the crater rim, about 85 m below the eruptive throat in the crater, and only 15 m lower than the old vent area at the southwest base of the cone.

The lava continued to cascade toward the north until April 10, when the sluggish flow solidified sufficiently to force the lava to break through, flood the top of the mound, and form a second cascade toward the northeast. These two cascades continued until the end of June, although the flow was not divided uniformly between the two and was carried mainly by one or the other at any given time. Bubbles of gas were erupted from the vent at several times during the period, and on January 17 one of these eruptions hurled pasty blobs of lava to a height of 60 to 80 m. Strong explosions in the main crater on March 23 were accompanied by a series of gas eruptions from the lava vent.

No lava activity was observed at the southwest base of the cone, although the area continued to furnish very hot gases at several places. As the lava is piled up thickly in this area and has been blanketed by ash for several years, it seems to have held its heat longer than in other areas. As a result, the rains that drench the lava field during the wet summer season are in part returned as steam, giving the area an eerie aspect for several months (see Fig. 6). This steam is nearly odorless, in contrast to the choking acid gases given off by the active flows.

Activity of the lava flows--The rate of flow down the lava cascades was as variable as usual. The cascade toward the north continued to supply the two lobes to the north-northwest of the cone that were active in December 1949. The westerly lobe obliterated completely the island of old ground to the north of old Parícutin village, and the other lobe covered a large part of the old ground to the southwest of San Juan Parangaricutiro (see Fig. 5). The fronts of these lobes were much higher than any that had been observed in former years, being probably more than 20 m high in some places (see Fig. 7). These fronts continued to move sluggishly at the end of the period. The flow from the northeast cascade moved slowly over the older lavas and had nearly reached the edge of the lava field at the base of Equijuata by the end of the period.

Fig. 6--Steam rising from ash-covered lava of December 1946 and earlier, in Mesa de los Hornitos area west of Parícutin cone; characteristic of this area through the rainy summer season; photographed on July 7, 1950

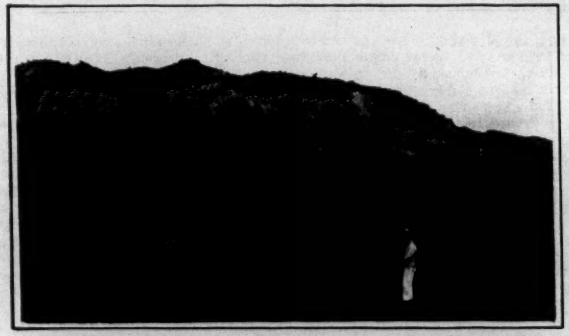


Fig. 7--High front of new lava overriding thin flow of February 1946, just northwest of old Parícutin village, on July 7, 1950

The area covered by the advancing lava from the north cascade amounted to about 1,656,000 sq m during the six-month period, and that covered by the lava from the northeast cascade was about 604,000 sq m, or a total of 2, 260,000 sq m. This compares with a total area of 2,640,000 sq m covered during the second half of 1949. Assuming that the average thickness of this lava is ten meters, which seems to be a reasonable figure, the total volume extruded in the first half of 1950 would be about 23 million cu m, in contrast to an estimated 25 million cu m in the preceding six months [FRIES and GUTIERREZ, 1950, p. 739]. In view of the errors that certainly enter into these calculations, it is not clear whether there has been an actual decrease in the rate of flow, but if so, it must have been small.

The total area covered by Parícutin lava at the end of June amounted to about 24.2 sq km, in contrast to the 22 sq km reported up to the end of 1946 [SEGERSTROM, 1950, p. 31].

Three strong fumaroles continued to deposit NH_4Cl on the lava to the southwest of San Juan Parangaricutiro (see Fig. 5) that came to rest in June 1948. Warm air still rises from some parts of the thin San Juan flow, which ceased moving more than five years ago.

Weather data--Monthly summaries of weather observations at Cuezeño Station and of rainfall at this and Equijuata Stations are given in Table 2. Total rainfall during the first half of 1950 was 425.7 mm at Cuezeño, and 594.3 mm at Equijuata. These figures compare with 324.3 mm at Cuezeño in the first half of 1949, and 516.3 mm at Equijuata. The rainfall at both stations thus exceeded considerably that of the corresponding period of the previous year, and the total at Equijuata continued to exceed that at Cuezeño. A comparison of yearly rainfall at Cuezeño from July 1946 to June 1950 is given in Table 3. Although the figure for 1946-1947 is much higher than the figures for the following three years, the differences shown are not believed to be related to changes in eruptive activity, for otherwise these figures should show a constant decline, as do those for ashfall at the same station.

April was again the driest month of the period, no precipitation being registered at either Cuezeño or Equijuata Stations. Dust storms were frequent during that month and obscured the Sun at times. Vegetation in the areas most subject to dust was severely injured as far as eight kilometers from the cone, but the limits of the completely devastated area do not seem to have been extended beyond those of a year ago. Mosses, lichens, and ferns have begun to invade moist places on the thinner lavas that came to rest as recently as four years ago. Some of these moist places represent extinct fumaroles, from which slightly warm, humid air still issues lazily. Some of the land near Angahuan that had lain idle since 1943 was returned to cultivation in May. One small area of forest from five to six kilometers to the north-northwest of the volcano was turned yellow by a moist ashfall in May, but few of the trees seem to have been killed. The ash covered the leaves and needles of the trees in the form of a fine mud, which may have suffocated the leaves and needles or perhaps have lowered the pH for sufficient time to kill a large part of them without killing the trees.

Acknowledgments--Continuous observations at Parícutin are being carried on by the United States Geological Survey, with funds of the Interdepartmental Committee on Scientific and Cultural Cooperation of the Department of State, in cooperation with the Comisión Impulsora y Coordinadora de la Investigación Científica of the Mexican Government. The salary of the junior author was carried partly by the Geological Society of America, partly by Richard E. Fuller; the junior author's assistant, Jesús Saldaña, was paid by the Mexican cooperating agency through Ing. Ezequiel Ordóñez, who unfortunately passed away early in February, and then through Ing. Ricardo Monges López, Director of the Instituto de Geofísica of the Universidad Nacional Autónoma of Mexico, whose close cooperation is greatly esteemed. Other expenses are being shared by the Geological Survey and the Comisión Impulsora. The writers wish to acknowledge observations made by Fred M. Bullard and Howel Williams while on brief visits to Parícutin in June. Both of these geologists had earlier studied and written about different aspects of the volcano, and their comments were therefore particularly welcome. Thanks are due to José Ramírez for the tedious work of drafting the diagrams and lava map.

References

WILCOX, RAY E., Activity of Parícutin Volcano from September 18 to November 30, 1946, Trans. Amer. Geophys. Union, v. 28, pp. 567-572, 1947.

SEGERSTROM, KENNETH, Erosion studies at Parícutin, State of Michoacán, Mexico, U. S. Geol. Surv. Bull. 965-A, pp. 1-164, 1950.

FRIES, CARL, JR., and CELEDONIO GUTIERREZ, Activity of Parícutin Volcano from July 1 to December 31, 1949, Trans. Amer. Geophys. Union, v. 31, pp. 732-740, 1950.

United States Geological Survey,
Paseo de la Reforma 64,
México, D. F., Mexico

(Communicated manuscript received October 12, 1950;
open for formal discussion until September 1, 1951.)

MOST FREQUENT PARTICLE PATHS IN A PLANE

Hermann von Schelling

Abstract--A model of plane continuous random motions is developed. The most frequent paths among these orbits are evaluated. A simple arrangement of them is discussed. The loci of points which have moved the same arc length from an original straight line seem to describe the dissipation of a vertical smoke column or the currents at the influx of a river into a lake. This success suggests that the most frequent particle paths are new elementary units from which various types of turbulent motions might be built up.

A particle moving with constant velocity in a horizontal plane is assumed to change the direction of its path at the end of each unit of time by an angle ϕ with the probability

$$f(\phi) = (1/\epsilon\sqrt{2\pi})\, e^{-\phi^2/2\epsilon^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where ϵ is the standard deviation of ϕ. It is known that such a particle has moved from the origin A to a point B with coordinates x_k, y_k in k units of time. No time is lost at the points of intersection.

It is proposed to find the most frequent path followed by the particle if the passage from A to B during k units of time has been repeated a great number of times. Paths with these conditions shall be called most frequent particle paths in the plane.

The total probability of the sequence $\phi_1, \phi_2, \ldots, \phi_k$ of changes in direction is

$$P = f(\phi_1)\, f(\phi_2) \ldots f(\phi_k) \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

if the ϕ_i are statistically independent. The probability P reaches a maximum in the case of a most frequent particle path. The same is true for $Q = \ln P$. Thus

$$Q = \sum_{s=1}^{k} \log_e f(\phi_s) = -(1/2\epsilon^2) \sum_{s=1}^{k} \phi_s^2 - k \log_e (\epsilon\sqrt{2\pi}) = \text{maximum} \ldots\ldots\ldots (3)$$

Let it be assumed that the particle has reached the origin A from the negative side of the x-axis. The path from A to B is then considered as a sequence of straight segments, the first of which makes an angle ϕ_1, the second an angle $(\phi_1 + \phi_2)$, and the k-th an angle $(\phi_1 + \phi_2 + \ldots + \phi_k)$ with the x-axis. Projection of these segments on the coordinate axes yield the equations

$$F = \cos\phi_1 + \cos(\phi_1 + \phi_2) + \ldots + \cos(\phi_1 + \phi_2 + \ldots + \phi_k) - x_k = 0 \quad \ldots\ldots\ldots (4)$$

$$G = \sin\phi_1 + \sin(\phi_1 + \phi_2) + \ldots + \sin(\phi_1 + \phi_2 + \ldots + \phi_k) - y_k = 0 \quad \ldots\ldots\ldots (5)$$

Let us consider the expression

$$\phi = Q + \lambda F + \mu G \ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

where λ, μ denote Lagrangian constants. For the most frequent particle path is

$$\partial\phi/\partial\phi_s = 0,\ s = 1, 2, \ldots, k \ldots\ldots\ldots\ldots\ldots\ldots (7)$$

which developed has the form

$$-\phi_s/\epsilon^2 - \lambda \sum_{u=s}^{k} \sin\left(\sum_{i=1}^{u} \phi_i\right) + \mu \sum_{u=s}^{k} \cos\left(\sum_{i=1}^{u} \phi_i\right) = 0 \quad \text{for } s = 1, 2, \ldots, k \ldots\ldots\ldots (8)$$

For simplifying we have to pass from the discrete to the continuous case. The writer was told that the problem is shifted by this passage and that a new definition of the "most frequent particle path" must be given. I would prefer to say that we have to translate the definition into the continuous language. May I anticipate that a later equation (10) together with (1) and (3) yields the following statement: A continuous curve which runs from A to B and has a given length is a most frequent particle path if

$$\int_A^B ds/\rho^2\,(s) = \text{minimum} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3a)$$

Here s is the arc length and $\rho(s)$ is the radius of curvature. We have only to substitute $\int$ for Σ in (3).

In order to transform the system (8) into a continuous equation, let us write

$$\alpha(s) = \phi_1 + \phi_2 + \ldots + \phi_s \qquad 1/\rho\,(s) = d\alpha(s)/ds = \phi\,(s) \quad \ldots\ldots\ldots\ldots \quad (9)$$

Here $\alpha(s)$ denotes the angle of the tangent to the curve, measured with respect to the positive x-axis. With these notations, the system of the k equations (8) is reduced to

$$(1/\epsilon^2)\, d\alpha/ds + \lambda \int_{u=s}^{k} \sin\,\alpha(u)\, du - \mu \int_{u=s}^{k} \cos\,\alpha(u)\, du = 0$$

Differentiating, multiplying by $2\, d\alpha/ds$ and integrating we find

$$(1/\epsilon^2)\,(d\alpha/ds)^2 + 2\,(\lambda \cos\alpha + \mu \sin\alpha) = 2C$$

This equation may be written

$$(1/\epsilon^2)\,(d\alpha/ds)^2 + 2c \cdot \cos\,(\alpha - \omega\,) = 2C$$

The angle ω stands for a rotation of the coordinate system and may be set equal to zero. If $c = 0$, the solutions consist of straight lines and circles. In the first case the motion is not disturbed at all. In the second case we have a whirlpool; the radial velocity increases as the center of the vortex is approached.

Let us consider the general solution. Then $c \neq 0$ and an appropriate choice of the units of ϵ and C enables us to get $c = 1$. Only the mean angular change and the constant C are characteristic in the equation above. Thus the normal form of the equation of the most frequent particle path in a plane is

$$1/\rho = d\alpha/ds = \epsilon \sqrt{2\,(C - \cos\alpha)} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (10)$$

The arc length s and the coordinates (x,y) of a point of the path are given by the following elliptic integrals

$$\left.\begin{aligned} \epsilon(s - s_0\,(C)) &= \int_\pi^\alpha [1/\sqrt{2\,(C - \cos\psi)}]\, d\psi \\ \epsilon(x - x_0\,(C)) &= \epsilon \int_{s_0}^{s} \cos\,\alpha\, d\sigma = \int_\pi^\alpha [\cos\psi/\sqrt{2\,(C - \cos\psi)}]\, d\psi \\ \epsilon(y - y_0\,(C)) &= \epsilon \int_{s_0}^{s} \sin\,\alpha\, d\sigma = \int_\pi^\alpha [\sin\psi/\sqrt{2\,(C - \cos\psi)}]\, d\psi = 1/\epsilon\rho - 1/\epsilon\rho_0 \end{aligned}\right\} \quad \ldots\ldots \quad (11)$$

The constants of integration are arbitrary if only one path is plotted which belongs to a given value of C. If we want to represent a whole set of most frequent particle paths, we have to make a choice. For simplifying the rather confusing picture let us assume

$$\epsilon s_0\,(C) = 0 \qquad \epsilon x_0\,(C) = 0 \qquad \epsilon y_0\,(C) = 1/\epsilon\rho_0 \quad \ldots\ldots\ldots\ldots \quad (12)$$

The second equation of (12) means that the y-axis is an axis of symmetry for the whole set of curves. According to the third, all points of inflection are on the x-axis. The length of arc is measured from the y-axis which is crossed perpendicularly by all curves from the positive to the negative side.

It has to be said that our original problem could have been solved by one or more particular paths which connect the given points and have the requested length. That is a boundary problem with which we would have to deal numerically. It is not worth while. More interesting is a survey of a whole set of most frequent particle paths. We are free in shifting the paths into a simple pattern which is similar to an observed flow. The system (12) is such a choice. It has surprising features.

Two cases will be studied.

First case

$$-1 \leqq C \leqq +1$$

With the notations

$$C = -\cos 2\gamma \qquad k = \sin\gamma \qquad \cos\alpha/2 = \sin\gamma \sin\phi$$

we get

$$\left.\begin{aligned} \epsilon s &= F(k, \phi) \\ \epsilon x &= F(k, \phi) - 2E(k, \phi) \\ \epsilon y &= 2k\cos\phi \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (11a)$$

Here $F(k, \phi)$ and $E(k, \phi)$ are Legendre's standard forms of elliptic integrals.

Second case

$$C > +1$$

We put

$$C = (1 + \cos^2\gamma)/\sin^2\gamma \qquad k = \sin\gamma \qquad \sin\alpha/2 = \cos\phi$$

The resulting formulas are

$$\left.\begin{aligned} \epsilon s &= k\,F(k, \phi) \\ \epsilon x &= -k\,F(k, \phi) + (2/k)\,(F(k, \phi) - E(k, \phi)) \\ \epsilon y &= (2/k)\sqrt{1 - k^2\sin^2\phi} \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (11b)$$

For any path the value of k is fixed; ϕ is the parameter of the representation. The value $\phi = 0$ belongs to $(s = 0;\ x = 0)$ for all curves.

If we want to compare our model with observed data, the most frequent particle paths are not convenient. They mingle and might not be separated from the observations. However, envelopes of most frequent particle paths or an eventual closed orbit would call our attention as particles are crowding on these lines which may be compared with caustic curves of geometrical optics.

Figure 1 shows the most frequent particle paths for the two cases studied for every 10° of the angle γ. One closed path exists in the first case for $\gamma = 65°\ 04'$; its shape is similar to a lemniscate. The orbits except those for $\gamma = 0°$ and $\gamma = 90°$ are periodic. Three periods have been drawn for all curves.

Envelopes of low order have been constructed graphically. The paths are crowding inside a mushroom-shaped region similar to dissipating smoke above a chimney or to a flow of a river into a lake perpendicularly to the shoreline.

Let us follow the particles which happen to be on the positive y-axis at zero time. We plot their location after 1, 2, 3, 4, 5, 6 units of time assuming that they travel the distance $\epsilon s = 1$ during the unit of time. These isochronal curves can be drawn easily since simple formulas for the arc length exist according to (11a) and (11b). Figure 2 shows the result. It may be instructive to turn the diagram upside down. If we compare the positive y-axis with smoke rising from a chimney into calm air, the isochronal curves reproduce the step by step disintegration of this column of smoke. It tilts while the upper half is condensed (1). Then it bends and grows longer (2).

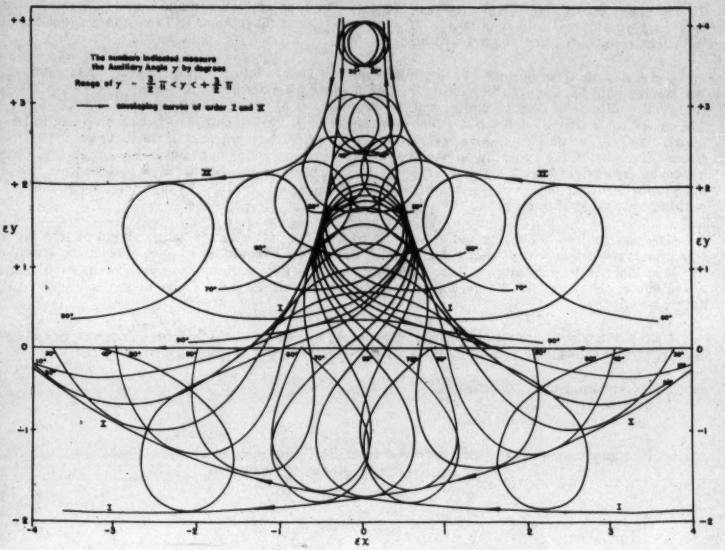


Fig. 1--Complete set of most frequent particle paths

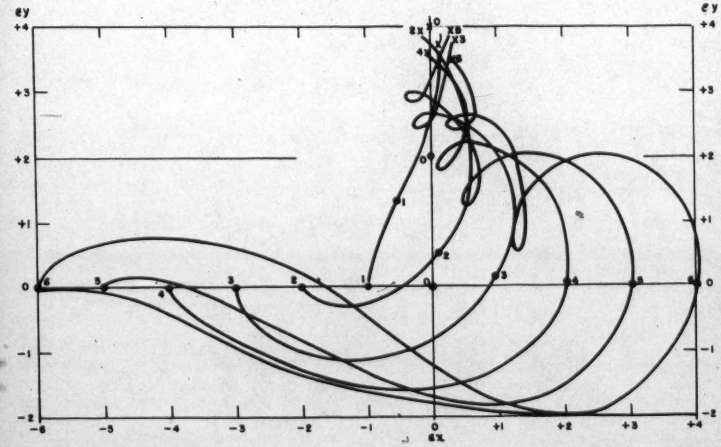


Fig. 2--Isochronal curves

This process continues; a first loop appears (3). The loop rises more and more (4-6), a second loop emerges (5) and goes up also (6). The curves (5) and (6) intersect the x-axis a second time, imitating another feature of wavering smoke.

Let us summarize how we get this mathematical representation of a familiar phenomenon. We started with the purely stochastical model of most frequent particle paths. The result was a family of orbits depending on one essential parameter C of which the range was $-1 \leqq C \leqq +\infty$. The cases $-1 \leqq C \leqq +1$ and $C > +1$ had to be separated. Now a completely new step had to be made. We tried to build up a known flow pattern by using the whole set of most frequent particle paths. Our choice (12), merely an hypothesis, was recommended because of its simplicity. Other arrangements might have been studied as well. It is to be supposed that flow patterns are different just in the distribution of the most frequent particle paths which are the elementary units building up a field of currents.

The equations (12) correspond apparently to the dissipation of a smoke column or to a river which intersects the shoreline of a lake perpendicularly. It would be easy to generalize (12) to the case that the stream hits the lake obliquely. That is just another example. Many further applications could be expected when the elementary quality of the most frequent particle path will have met approval.

Opinions and conclusions contained in this paper are those of the author. They are not to be construed as necessarily reflecting the views or endorsement of the Navy Department.

Naval Medical Research Laboratory,
U. S. Submarine Base,
New London, Connecticut

(Communicated manuscript received March 1, 1950, and, as revised, February 19, 1951; open for formal discussion until September 1, 1951.)

Transactions, American Geophysical Union Volume 32, Number 2 April 1951

THE ROLE OF AQUIFERS IN WATER SUPPLY

Raphael G. Kazmann

Abstract--The concept of "safe yield" is analyzed, and it is shown that, instead of having a single value in any given hydrogeologic situation as has been assumed, it has many possible values; hence, it is not a useful concept. As an alternate approach to the problem of perennial ground-water supply, the functions of aquifers are stated, the tasks of the science of hydrogeology are outlined, and it is shown that by means of hydrologic engineering based on permissive legislation, legislation which is compatible with the doctrine of appropriation, withdrawals of ground water can be increased to almost any desired extent without danger of aquifer depletion.

In recent years the utilization of underground water has increased greatly. Simultaneously the accompanying fall in ground-water levels has focused public attention on the real or potential "overdevelopment" of ground-water supplies in some areas. In some parts of the West, where the importance of water has been most keenly recognized, legal doctrines regarding the appropriation and use of surface water have been enlarged and extended in an attempt to control ground-water withdrawals.

All of the engineering and legal thinking has been based on the idea of the perennial withdrawal of ground water. This has reflected the thinking of hydrogeologists and other workers in the field of ground water on the "safe yield" or optimum rate of perennial withdrawal of water from aquifers. The following definitions, taken almost at random from reports, books, and papers on ground water covering the past 30 years, mirror the most advanced thinking in the field of hydrogeology during the period.

Definitions of safe yield--Some of these definitions include economic considerations, others specifically exclude them, others just do not mention economics. Included are definitions by private consultants and state and federal authorities. It may not be too much to say that, at one time or another, every professional worker in the field of hydrogeology has felt dissatisfied with the existing definitions of "safe yield" or "perennial rate of water withdrawal" and has tried to frame a more suitable definition. All of the definitions quoted below have points of similarity and, equally, significant points of difference:

"The safe yield of an underground reservoir (is) the practicable rate of withdrawing water from it perennially for human use." [MEINZER, 1920; TOLMAN, 1937, p. 473]

"The safe yield of an aquifer, or any part of it, is the amount of water it will yield indefinitely without impairing the quantity or quality of the supply. In order that the safe yield may not be exceeded, the withdrawal of water from an aquifer must not exceed the rate at which it can be recharged nor the rate at which it can transmit water (presumably from the recharge area to the area of withdrawal - author)." [BARKSDALE, 1943]

"The safe yield of a water-bearing formation is the maximum rate at which water may be withdrawn without impairing the quantity or quality of the supply. In an artesian system such as the Pennsylvanian sandstones, the safe yield is limited by the transmissibility of the sandstones, the intake capacity of the sandstones, the amount of water that can be taken from storage, and the danger of chemical contamination by water from formations below. Accurate determinations of these limiting conditions require an extensive study of the entire aquifer which, in this case, covers most of central Michigan." [STUART, 1945, p. 28]

"Safe yield is the annual extraction from a ground-water unit which will not, or does not, (1) exceed the average annual recharge; (2) so lower the water table that permissible cost of pumping is exceeded; or (3) so lower the water table as to permit intrusion of water of undesirable quality." [CONKLING, 1946, p. 238]

"The safe yield of a ground-water basin is that quantity of usable water which can be extracted therefrom each year without progressive lowering below the level at which the same quantity can be obtained at reasonable cost." [HILL, 1946, p. 307]

"The perennial yield of the aquifer underlying an area of ground-water development has been regarded as the maximum rate at which water can be salvaged from the natural discharge, or added to the recharge, or both . . . . In some reports the economical pumping lift has been considered to be a factor in this definition; however, the economics of recovery seem to be irrelevant to the determination of the quantity of water which an aquifer will yield and so are not considered here." [WILLIAMS and LOHMAN, 1949, p. 212]

Purpose and interpretation of "safe yield" definitions--The purpose of these definitions of "safe yield" is to further the cause of conservation of the Nation's ground-water resources. In this connection the word "conservation" is taken to mean the obtaining of "maximum beneficial use for an indefinitely long period of time." This concept of conservation, not necessarily limited to the utilization of underground water, is entirely compatible with the legal doctrine of appropriation and is used as the basis for the following discussion.

The differences of opinion as to which factors are to be included in a definition of "safe yield" tend to obscure the two fundamental points on which all definitions are in agreement.

(1) The whole aquifer (basin) (unit) is considered as a unit from the intake area to the area of water withdrawals. (This interpretation is considered valid despite the suggestion in the Barksdale and Williams-Lohman definitions that "part of it", or "the aquifer underlying an area of ground-water development", can have a "safe yield" without consideration of the recharge area outside the area of pumping. All other definitions are unambiguous on this point: the entire water-bearing formation is treated as a unit.)

(2) The concept that the water withdrawn at the critical rate is going to be used by people, that is, that the greatest concentration of ground-water pumpage can be expected at or near the point of use.

Now, since the geometry of withdrawal, that is, the well field and the position of the area of ground-water withdrawals depends on economics or politics and not hydrogeology, the definitions given above covering "safe yield" become logically untenable since, in a given aquifer, it is possible to conceive widely varying "safe yields" depending merely on the position of water withdrawals relative to the area of recharge. There is, thus, no single, fixed limiting quantity to be termed an aquifer's "safe yield." This contradiction in terms, subconsciously recognized by all hydrogeologists, has probably been responsible for the multitude of published definitions of "safe yield" and the innumerable unpublished attempts to pin the meaning down. Administrators of water laws who have to protect the rights of water appropriators and prevent the development of ground-water supplies from exceeding the "safe yield" of specific aquifers are attempting to do something which is inherently impossible, since the "safe yield" of a single aquifer has different magnitudes from place to place in the same aquifer, depending on the position of withdrawals.

For example, a well field near the outcrop area of an aquifer, which is on contact with a stream will have one yield, depending primarily on the steady state mean hydraulic gradient. The identical well field, if located ten times as far from the stream, assuming the same available head, will have one-tenth the hydraulic gradient to the outcrop area, and, roughly, one-tenth the steady state output. The same well field occupying any intermediate position will have an intermediate water output. Hence, for a given aquifer there is no single figure which can be termed the "safe yield" since the same aquifer will yield, perennially, a number of different quantities, depending on where the well field is placed. In the foregoing discussion, for purposes of simplification the well field is assumed to be parallel to the source of recharge and is idealized as a trench operating at the same mean drawdown.

The functions of aquifers--In the following discussion the aquifers are assumed to be composed of porous material (sand and gravel). As will become apparent, limestone and basalt aquifers are excluded from parts of the following discussion.

Aquifers perform three primary functions: (1) They act as natural slow-sand filters at their intake areas (outcrops). This might be called their "filter plant" function. (2) They transmit water from the intake area to the point of withdrawal. This might be termed their "pipe line" function. (3) They store water. This might be termed their "reservoir" function.

These three functions are not equally useful. In certain areas the reservoir function is most important, whereas in other areas the filter plant function is paramount. Ground-water legislation which treats aquifers as units and ignores their functions is falsely premised and will create as many problems as it solves.

Aquifers as reservoirs--The reservoir function of aquifers is probably the primary function in areas of intermittent stream flow or in areas solely dependent on direct rainfall infiltration. Under such circumstances, storage is vital, be it above ground or underground. It is of interest to note that the Nation's usable subsurface storage, in the aggregate, far exceeds the storage available in surface reservoirs. Moreover, in contrast with surface reservoirs, subsurface storage is affected less by evaporation (and transpiration), sedimentation is not a problem and valuable land is not removed from productive uses through flooding.

In order to make the best use of aquifers for storage purposes it will be necessary to develop artificial recharge through wells or other man-made structures. There are sound reasons for believing that artificial recharge may be accomplished through certain types of wells with surface water that has received nothing more than primary sedimentation, through the use of suitably designed backwashing devices. In any event, special filtration plants can be built to produce water of a quality suitable for artificial recharge; the governing considerations are economic and political, not scientific or technologic.

The application of artificial recharge near the points of ground-water use will enable water levels to be held between any predetermined elevations and thus enable the best use to be made of our water resources.

In view of the above it may well be that the principal tasks of hydrogeology, in connection with the reservoir functions of aquifers, should be to determine the existence of all the aquifers underlying the areas of interest; the boundaries of the aquifers and their storage and transmissibility coefficients; the existence and location of beds which might produce saline or mineralized waters; the areas of outcrop of each aquifer, if any; the sources, or potential sources, of recharge; and the chemical and thermal characteristics of the water of each aquifer.

With all of the foregoing information, it will be possible for the hydrologic engineer to study the water-resources problems of an area with full knowledge of the reservoir characteristics of the aquifers underlying it and, consequently, design his structures for the perennial withdrawal of predetermined quantities of water. In the past this has been an infrequent occurrence, the engineers having confined themselves to surface reservoir sites, ignoring the potentialities of the hydrogeologic situation.

Aquifers as filter plants--Along the polluted streams of the East which traverse aquifer outcrops, the filter-plant function of aquifers is probably the most valuable at present. However, in recent years, as surface reservoir sites have become scarcer, the utility of subsurface storage has increased in importance and this statement should be understood as being strictly applicable to the current situation.

On the basis of personal experience covering the use of aquifers as natural filter plants, these aquifers having a total water production rate of about 250 mgd, the writer's observations have been that (1) the aquifer removes all mechanically suspended or colloidally suspended particles, and (2) the aquifer removes organic compounds, tastes, and odors as well as pathogenic organisms from infiltrated water, probably through some sort of bacterial action, at the aquifer-water intersurface.

The principal tasks of hydrogeology in connection with the filter-plant functions of aquifers include mapping the aquifer and the area of recharge, determining whether and when the aquifer is in contact with surface-water bodies in its area of outcrop, determining the hydrogeologic constants of the aquifer and the boundaries of the aquifer, and determining the quality of water in the other aquifers in the area which might have some effect on its use as a natural filter plant.

With this information, the hydrologic engineer can plan a system of water withdrawal and subsurface storage utilization to take care of the variations in quantity and quality of the surface source, be it precipitation on the limited outcrop area, or infiltration from a river or lake which collects the precipitation from a large area. Available data on rainfall and runoff can be studied with the view of making the utmost use of the filter-plant qualities of aquifers.

Legal doctrines--The detailed discussion of legal doctrines needed to further water conservation is beyond the scope of this paper but, suffice it to say, those doctrines are enforceable if based on the functions of aquifers as outlined previously in this paper. In some states legislation has already been passed and is available for use with only minor modification. In the following paragraphs, it is assumed that the doctrine of appropriation is the basic water law.

Users of ground water whose property abuts on a stream and who are using the aquifer's filter-plant functions should be placed in the same general category as the water appropriator who pumps directly from the stream.

Users of ground water who are pumping primarily from storage should be required to file notice of their water withdrawals but would not receive any appropriative right at that time. Any one who so desired, could put down a well and begin to withdraw water. If past experience is any guide, the rate of water withdrawal in the area will increase and then exceed the natural replenish-

ment. Water levels may be expected to decline, pumping costs to rise and, possibly, the well yields to fall.

Assuming that there were no dangers of aquifer contamination, the legislation would make possible the creation, on local initiative, of water districts or authorities. The purpose of such a district or authority would be to apply for the right to appropriate surface water and to recharge the aquifer with this water. If water were available, the State Water Administrator would allow appropriation at the minimum rate necessary to satisfy the average annual demand. That is, if the water were used for irrigation during 100 days a year at the rate of A cubic feet per second, the average annual recharge rate might be (100) (A)/365 cfs and the aquifer storage would be used to satisfy peak demand. If the local people did not desire to create a district or authority, the State Water Administrator would do nothing and let events take their course.

If there were danger of permanent damage to the aquifer because of the intrusion of mineralized water, the State Water Administrator would place two alternatives before the ground-water users: either form a district and recharge the aquifer (as outlined in the preceding paragraph) or cut the rate of pumpage to the point where permanent injury to the aquifer would be prevented.

Conclusion--An attempt has been made to show that the concept of "safe yield" as used by many hydrogeologists and other workers in the field of ground water, is not soundly based. The perennial withdrawal of water from an aquifer must be matched by the perennial replenishment of the aquifer in the area of use. Since such replenishment can be controlled, almost at will, and depends on engineering, economic, and legal considerations, the hydrogeologist cannot be concerned with determining what the magnitude of the perennial withdrawal should be. It is proper and necessary, however, that the hydrogeologist point out areas where ground-water withdrawals under existing conditions exceed the natural replenishment, that is, the replenishment without the construction and replenishing operations involved in artificial recharge.

As a matter of policy it is questionable whether the curtailment of ground-water withdrawals is the principal, or more desirable, solution to the problem of "over-development." In most areas this is the least desirable solution if the maximum beneficial use of our water resources is to be obtained.

It should be emphasized that the ground-water resources of an area cannot be evaluated apart from the surface-water resources of the same area. The identical particle of water may, at different times, be part of the ground-water body and the surface-water body. Surface and ground water are inextricably intertwined and are not to be arbitrarily separated. The possibilities of utilizing our water resources more efficiently are invariably bound up in economic and engineering realities. These, in turn, are not limited to discovering and utilizing the unassisted efforts of nature any more than road building in mountainous terrain is confined to following the natural contours of the land surface.

References

BARKSDALE, HENRY C., MEREDITH E. JOHNSON, ROGER C. BAKER, EDWARD J. SCHAEFER, and GEORGE D. DEBUCHANANNE, The ground-water supplies of Middlesex County, New Jersey, New Jersey Water Policy Comm., Spec. Rep. 8, 1943.

CONKLING, HAROLD, Utilization of ground-water storage in stream system development, Trans. Amer. Soc. Civ. Eng., v. 111, 1946.

HILL, RAYMOND F., discussion of Utilization of ground-water storage in stream system development, Trans. Amer. Soc. Civ. Eng., v. 111, 1946.

MEINZER, O. E., Quantitative methods of estimating ground-water supplies, Bull. Geol. Soc. Amer., v. 31, pp. 329-338, 1920.

STUART, W. T., Ground-water resources of the Lansing area, Mich. Dept. Cons., Geol. Surv. Div., Prog. Rep. 13, 1945.

TOLMAN, C. F., Ground water, McGraw-Hill Book Co., 1937.

WILLIAMS, C. C., and S. W. LOHMAN, Geology and ground-water resources of a part of south central Kansas, Geol. Surv. Kansas, Bull. 79, 1949.

2284 Lehner Road,
Columbus 11, Ohio

(Manuscript received May 9, 1950; presented at the Thirty-First Annual Meeting, Washington, D. C., May 1, 1950; open for formal discussion until September 1, 1951.)

Transactions, American Geophysical Union Volume 32, Number 2 April 1951

A GENERAL FORMULA FOR HYDROLOGIC FREQUENCY ANALYSIS

Ven Te Chow

Abstract--A general formula is presented to simplify many existing methods of hydrologic frequency analysis. It is shown that the methods differ only in the definition of the frequency factor contained in the formula. The derivation of the formula is simple, and does not require familiarity with advanced mathematics and statistics. The application of the formula is practical so that it provides a valuable tool for the hydrologic design of hydraulic structures.

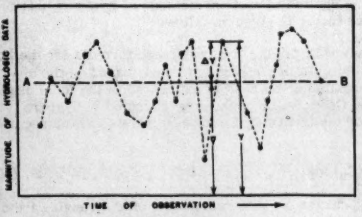


Fig. 1--Chronological plottings of hydrologic data

The formula--In a chronological chart as shown in Figure 1, the magnitude, y, of hydrologic data is plotted against the time order of observations. The horizontal line AB indicates the position of the mean, $\bar{y}$, of all observed data. If N is the total number of the observed data, then the mean is computed by the formula

$$\bar{y} = \Sigma y/N \quad \ldots\ldots\ldots\ldots (1)$$

It is evident from the chart that any particular value of y is composed of two parts, namely, the mean, $\bar{y}$, and the departure from the mean, Δy; or

$$y = \bar{y} + \Delta y \quad \ldots\ldots\ldots\ldots (2)$$

The departure from the mean may be positive or negative, large or small, being very irregular and variable. From a statistical point of view, this quantity possesses the following two important properties: (1) the tendency to deviate from the mean; and (2) the frequency of occurrence.

The first property has been widely investigated by BINNIE [1892]. By statistics, this property can be measured by a parameter called the standard deviation, σ, which is defined by

$$\sigma = \sqrt{[N/(N-1)]\,(\overline{y^2} - \bar{y}^2)} \quad \ldots\ldots\ldots\ldots (3)$$

where $\overline{y^2}$ is the mean of the squares of y, or

$$\overline{y^2} = \Sigma y^2/N \quad \ldots\ldots\ldots\ldots (4)$$

N and $\bar{y}$ are defined as before.

The second property was first studied by FULLER [1914]. This property is to be measured by a term called the frequency factor, K, which depends upon the law of occurrence of a particular hydrologic event under consideration. This factor is to be related to a recurrence interval, T, which is defined as the average time interval in years within which a given event will be equaled or exceeded. All K-T-curves in this paper are shown in a semi-logarithmic relation in which K is plotted on the linear scale and T on the logarithmic scale.

The frequency factor for various methods (as will be verified later) is so defined that the departure from the mean is equal to the product of the standard deviation and the frequency factor, or

$$\Delta y = \sigma \cdot K \quad \ldots\ldots\ldots\ldots (5)$$

Hence, (2) may be written

$$y = \bar{y} + \sigma \cdot K \quad \ldots\ldots\ldots\ldots (6)$$

Dividing each term by $\bar{y}$

$$y/\bar{y} = 1 + C_v K \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

in which $y/\bar{y}$ is called the y-mean ratio, and C_v is a coefficient of variation which is equal to the ratio of the standard deviation to the mean, or

$$C_v = \sigma/\bar{y} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

From (3)

$$C_v = \sqrt{[N/(N-1)](\overline{y^2}/\bar{y}^2 - 1)} \quad \ldots\ldots\ldots\ldots\ldots\ldots (9)$$

Eq. (7) is the general formula for hydrologic frequency analysis. This formula is applicable to many existing methods of hydrologic frequency analysis. The frequency factor in this formula is verified as below.

Verification of frequency factor--When (7) is applied to various methods of hydrologic frequency analysis, the verification of the frequency factor is given as follows:

(1) Fuller Method. FULLER [1914] is given credit for the first published formula for the hydrologic frequency analysis of flood flows. His formula is strictly empirical, based on the observed data of many streams. However, this formula can be readily expressed in the form of (7) in which y is the most probable maximum annual flood, 24-hr peak, to be expected in T years, $\bar{y}$ is the average of the maximum annual floods, and the frequency factor K is related to the recurrence interval in T years by

$$K = (0.8/C_v) \log_{10} T \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (10)$$

Based on the relation expressed by (10), the K-T-curves for different values of C_v, ranging from 0.1 to 2.0, are prepared as shown in Figure 2. As the most common value of C_v in Fuller's study is 0.50, the corresponding K-T-curve is shown by a heavy line.

(2) Hazen Method. HAZEN [1930] has developed empirically a table of factors for computing flood frequencies by means of two statistic parameters, namely, the coefficient of skewness, C_s, and the coefficient of variation, C_v. The coefficient of skewness is computed by

$$C_s = [\overline{y^3} - 3\bar{y}\,\overline{y^2} + 2\bar{y}^3)/\bar{y}^3 C_v^3 (1 - 1/N)]\, F \quad \ldots\ldots\ldots\ldots\ldots (11)$$

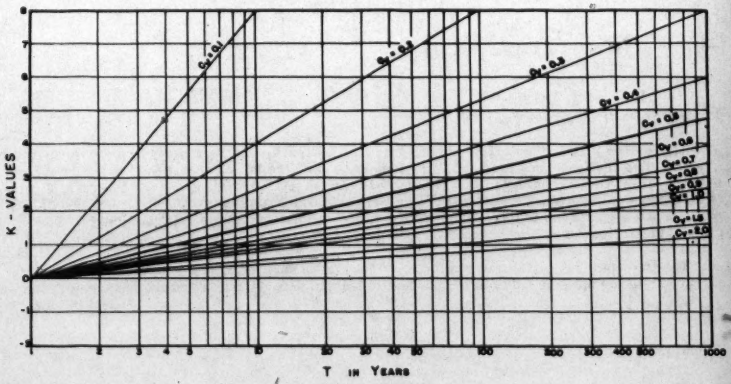


Fig. 2--K-T-curves for Fuller method

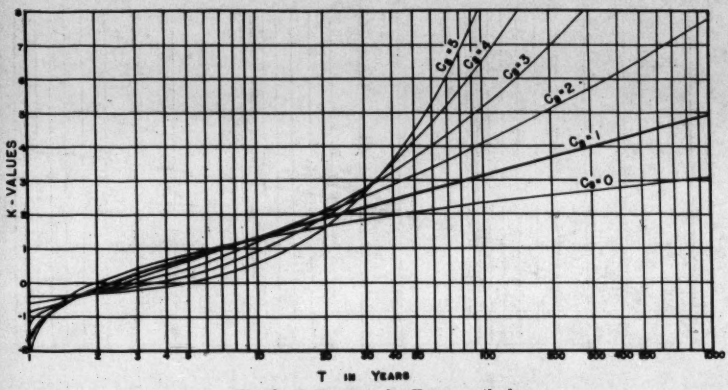


Fig. 3--K-T-curves for Hazen method

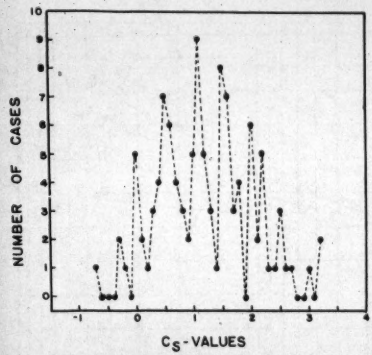


Fig. 4--Distribution of C_S values for 109 streams

where $\overline{y^3}$ is the mean of the cubes of y, or

$$\overline{y^3} = \Sigma y^3/N \quad \ldots\ldots\ldots \quad (12)$$

and F is a factor for adjusting the influence of the length of record, or

$$F = 1 + 8.5/N. \quad \ldots\ldots\ldots \quad (13)$$

It can be shown that the Hazen method can be expressed by means of (7), in which y is the maximum annual flood in cubic feet per second to be expected in T years, $\bar{y}$ is the average of the annual floods, and the frequency factor is equivalent to Hazen's tabulated factors. Based on the latter relation, the K-T-curves are constructed as shown in Figure 3 for various values of C_S.

Figure 4 shows the distribution of C_S values for the runoff of 109 different streams studied by Hazen. It is evident that the most frequent value of C_S is close to 1.0, the heavy line of Fig. 3.

Hazen's and some other methods require the computation of the coefficient of skewness. However, SLADE [1936b] has pointed out that because of errors of sampling inherent in the ordinary hydrologic data, it is meaningless to compute any statistical constants higher than the second moment, that is, the standard deviation. Therefore, it s suggested that the K-T-curve for $C_S = 1.0$ be used for all cases.

(3) Foster Method. FOSTER [1924] has developed a method which follows practically the same procedure as the Hazen method except that the computation of the tabulated factors are bs on the Pearson's skew frequency curves of Type I and Type III. Thus, the K-values in (7) are equal to the Foster's tabulated factors. The K-T-curves for the Foster method are constructed as shown in Figures 5 and 6. The coefficient of skewness is computed by (11) in which the F-value for the curve of Type I is computed by (13) and the F-value for the curve of Type III by the formula

$$F = 1 + 6/N. \quad \ldots\ldots\ldots \quad (14)$$

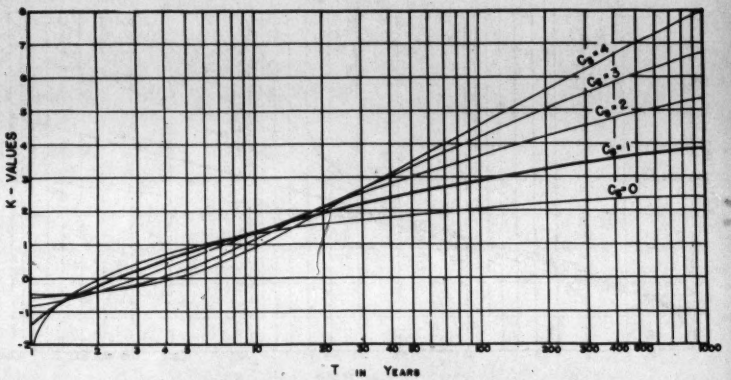


Fig. 5--K-T-curves for Foster method, Type I

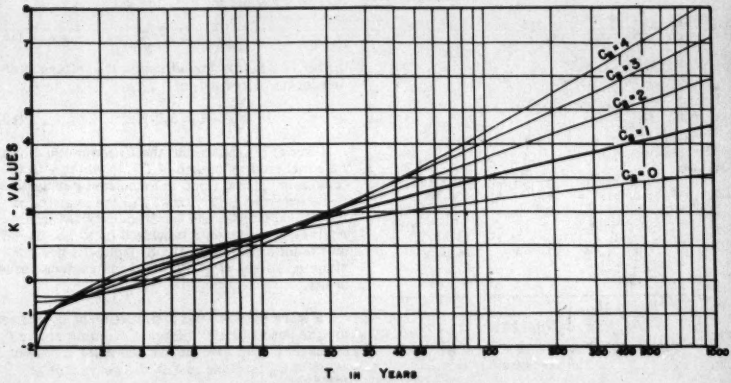


Fig. 6--K-T-curves for Foster method, Type III

In Figures 5 and 6, the K-T-curves for $C_s = 1.0$ are drawn in heavy lines. For the normal frequency distribution, $C_s = 0$.

(4) Slade Method. SLADE [1936a] has developed a method of hydrologic frequency analysis in which a totally bounded curve of distribution defined by a special asymmetric probability function is employed. This method can be formulated by (7) in which y is the magnitude of the hydrologic event, $\bar{y}$ is the mean of y, and K, the frequency factor, is equal to the parameter t used by Slade.

Based on Slade's table of t-values corresponding to the percentage of time for various values of θ and λ, the K-T-curves for $\theta = 10, \lambda = 2$; $\theta = 10, \lambda = 10$; $\theta = 1, \lambda = 10$; and $\theta = 1, \lambda = 2$ are constructed as shown in Figure 7. θ and λ are defined by Slade as $\lambda = b/\sigma$ and $\theta = g/b$, in which b and g are the parameters that correspond respectively to the maximum lower and maximum upper durations of the statistics from the mean, and σ is the standard deviation.

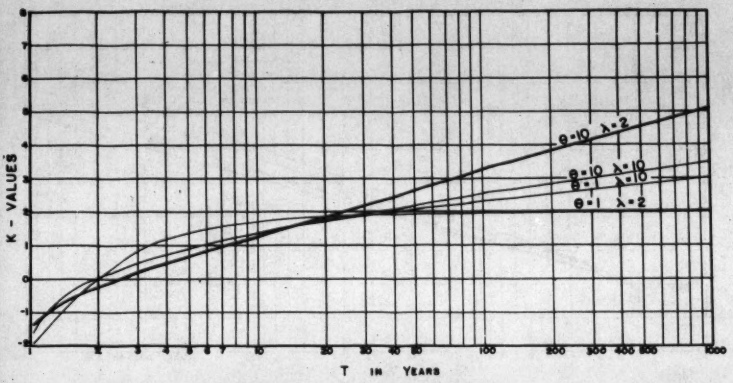


Fig. 7--K-T-curves for Slade method

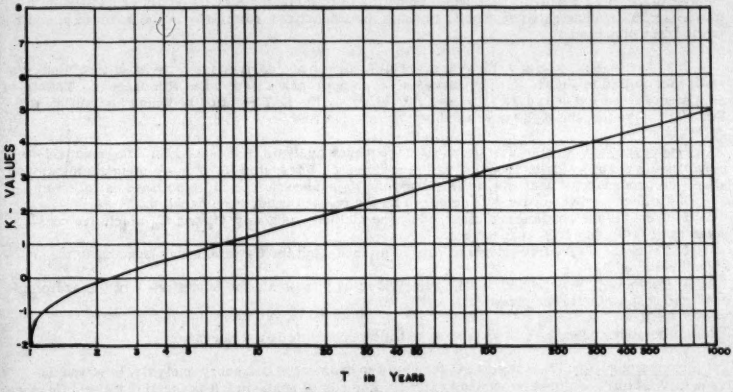


Fig. 8--K-T-curve for Gumbel method

(5) Gumbel Method. GUMBEL [1941] has developed a method for computing annual flood frequency based on the theory of largest values. POWELL [1943] has simplified the method for practical uses. This method can be expressed by (7) in which y is the largest daily stream discharge in a 365-day period, $\bar{y}$ is the mean of y, and K is the frequency factor expressed in terms of T as

$$K = -\sqrt{6}\left\{\gamma + \log_e [\log_e T - \log_e (T - 1)]\right\}/\pi \quad \ldots\ldots\ldots\ldots (15)$$

where $\gamma = 0.5772157$, a so-called Euler's constant. A plot of this formula gives the K-T-curve as shown in Figure 8.

(6) Potter Method. POTTER [1949] has simplified the Gumbel method by making a study of 370 Gumbel probability curves which are based on data of maximum rainfall intensities for various time periods, monthly and annual rainfall amounts, and peak rates of surface runoff. For a given

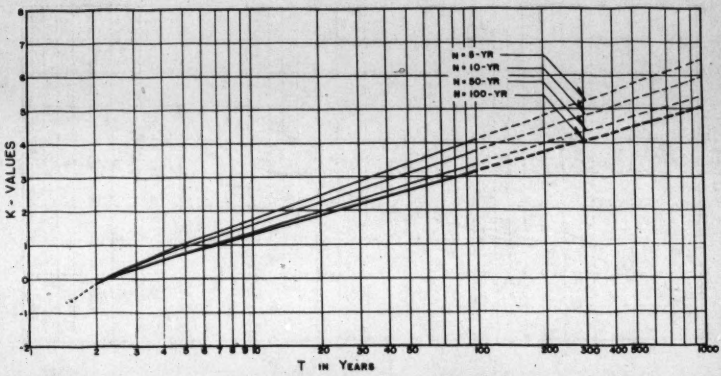


Fig. 9--K-T-curves for Potter method

number of years of record, N, the basic principle of this method may be easily expressed by (7) in which y is the peak rates of runoff, amounts, or intensity of rainfall; $\bar{y}$ is the mean of y; and K is the frequency factor.

For N = 5-, 10-, 50-, and 100-years, the K-T-curves are derived from the results of Potter's study and plotted in Figure 9. The curves seem to approach a limit when N increases. That is to say, when the period of record increases, its effect on the K-T-relation becomes insignificant. For N = 100 years, the K-T-curve is shown by a heavy line.

Procedure of analysis--The hydrologic frequency analysis is meant to find the magnitude y of a hydrologic event which is assigned with a recurrence interval of T. For all methods mentioned above the procedure of analysis, when (7) and the K-T-curve are used, is outlined as follows:

(1) Collect the hydrologic data required by the method under consideration.

(2) Compute the parameters required by the method; such as $\bar{y}$, C_v and C_s which are computed by (1), (9), and (11), respectively.

(3) From the K-T-curve prepared for the method, find the K-value corresponding to the assigned value of T.

(4) Compute $y/\bar{y}$ by (7) and multiply this value by $\bar{y}$ to obtain the magnitude y of the hydrologic event corresponding to the given value of T.

As the above procedure is very easy to follow, example is not necessary.

Conclusions--Eq. (7) is a general formula for hydrologic frequency analysis, in which the frequency factor is defined by various existing methods of analysis. It is found that the difference among the methods is simply the difference in the definition of the frequency factor implied by each method. However, detailed descriptions of various methods mentioned in this paper are not given, since they may be referred to in the cited references.

The data to be used are the annual values or annual maxima, or whatever it may be depending on the kind of method to be employed.

It is interesting to notice that the K-T-curve prepared for the Gumbel method agrees closely with the K-T-curves drawn in heavy line for other methods. As the Gumbel method has been applied to many hydrologic phenomena with satisfactory results, it is recommended that its K-T-curve is a best choice for the use of (7).

Discussions on the frequency viewpoint in dealing with problems of hydrology are beyond the scope of this paper. However, it seems desirable to mention that the frequency analysis, if properly handled and conservatively interpreted, is a valuable hydrologic tool. It is useful particularly

for the economic study of many hydraulic structures which are designed to take care of the hydrologic events.

References

BINNIE, ALEXANDER R., On mean or average rainfall and the fluctuation to which it is subject, Proc. Inst. Civil Eng., v. 109, pp. 89-172, 1892.

FOSTER, H. A., Theoretical frequency curves, Trans. Amer. Soc. Civil Eng., v. 87, pp. 142-173, 1924.

FULLER, WESTON E., Flood flows, Trans. Amer. Soc. Civil Eng., v. 77, pp. 564-617, 1914.

GUMBEL, E. J., The return period of flood flows, An. Math. Statis., v. 12, no. 2, pp. 163-190, 1941.

HAZEN, ALLEN, Flood flows, John Wiley, 199 pp., 1930.

POTTER, W. D., Simplification of the Gumbel method for computing probability curves, U. S. Geol. Survey, Soil Conservation Service, Washington, D. C., 22 pp., 1949.

POWELL, R. W., A simple method of estimating flood frequencies, Civil Eng., v. 13, pp. 105-106, 1943.

SLADE, J. J., An asymmetric probability function, Trans. Amer. Soc. Civil Eng., v. 101, pp. 35-104, 1936a.

SLADE, J. J., The reliability of statistical methods in the determination of flood frequencies, U. S. Geol. Survey, Water Supply Paper 771, pp. 421-432, 1936b.

Department of Civil Engineering,
University of Illinois,
Urbana, Illinois

(Communicated manuscript received October 4, 1950;
open for formal discussion until September 1, 1951.)

Transactions, American Geophysical Union Volume 32, Number 2 April 1951

PROGRESSIVE WAVES IN NON-ARTESIAN AQUIFERS

P. Wilh. Werner and Daniel Norén

Abstract--The present study deals with progressive waves in ground-water aquifers under water-table conditions. The theory developed aims at clarifying the characteristics of the non-steady flow in question. Moreover, it gives the clue to the determination of certain basic factors in the natural ground-water control, and to the explanation of some phenomena concerning the relation between subsurface runoff and replenishment or rainfall.

Introduction

Many geophysical problems, as well as the ever-increasing use and value of ground water for engineering, agricultural, and other purposes, make the importance of a thorough knowledge about the general behavior of natural aquifers more and more pronounced. Of great interest in this connection are the time effects occurring in a major aquifer when some of the boundary conditions are changed in some way or other. Such changes may be caused by climatic variations, by geological processes, by seasonal fluctuations, or by artificial measures.

This paper will deal with progressive waves caused by periodic variations in a major non-artesian aquifer of comparatively great depth, having no visible storage and a low rate of recharge from surface infiltration. Such conditions often occur in localities with dry climate; the theory is thus specially applicable to arid or semi-arid regions, although as a more or less rough approximation it may also be applied to other conditions.

Motive fluctuation

The "motive fluctuation," in the sense of the following investigation, is the immediate agent acting on the ground-water body. It may be of different types, and may have various sources [VEATCH, 1906, p. 28]. As far as non-artesian aquifers are concerned it is mostly bound to the tail water level or to the replenishment.

Periodic variations in the tail water level may be due to natural causes (such as tides, seiches, and changes in river stage) or to artificial measures (such as discharge regulation through a dam).

As regards the replenishment, daily and other short-term fluctuations are often due to temperature variations, causing changes in evaporation and transpiration. The motive fluctuation may then nearly approach the harmonic type (see Fig. 1). The most important fluctuations of this kind, however, are the annual fluctuations, which are chiefly dominated by the precipitation [VEATCH, 1906, pp. 29-52]. Even secular fluctuations have been observed in nature [PRINZ, 1923, p. 98; McDONALD and LANGBEIN, 1948], but they are not easily discernible, unless the observations cover a rather long period.

Although the motive fluctuations in natural aquifers are seldom, if ever, truly harmonic, particular attention will be paid to this type, as it most clearly shows the fundamental characteristics of the non-steady flow in question. It may be mentioned in this connection that the problem of periodic fluctuations other than harmonic may be solved, using the Fourier Theorem, by superposition of solutions of the type given below.

Theory

Notation--The following notation is used in this paper:

L = length of ground-water stream (m)
x = coordinate of length
z = ground-water level (m), unaffected by capillary rise
h = tail water level (m)
H = weighted mean depth (m) of ground-water stream

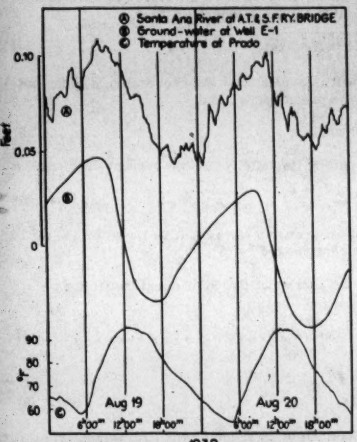


Fig. 1--Effect of evaporation and transpiration on river and ground-water elevations, Santa Ana River [according to TROXELL, 1936]

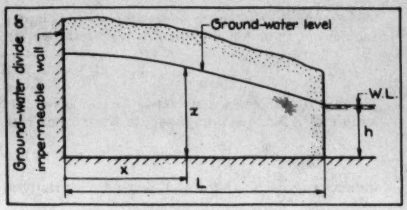


Fig. 2--Schematical profile of non-artesian aquifer

p = rate of replenishment (m/sec), taken positive as recharge and negative as draft
t = time (sec)
c = Darcy's transmission constant (m/sec)
ϵ = "effective" pore space, as a decimal fraction (see text)
$k = cH/\epsilon$ = "viscosity factor" (m^2/sec) (see text)
a = amplitude of fluctuation (m) in tail water level
b = amplitude of fluctuation (m/sec) in replenishment
T = period of fluctuation (sec)
$\theta = 2\pi/T$ = "speed" of fluctuation (sec^{-1})
μ = arbitrary number
n = integers 0, 1, 2, 3 . . .
$i = \sqrt{-1}$ = unit of imaginary numbers
e = base of natural logarithms

Differential equation--A non-artesian ground-water stream is schematically shown in Figure 2. For the purpose of the investigation it may be assumed that the aquifer is one-dimensional and homogeneous, and that the bottom is horizontal.

Barring the case of very small lengths of the ground-water stream such as exist in the seepage through dams, the ground-water calculations may, with sufficient accuracy, be based on Dupuit's approximate assumption of a constant hydraulic gradient in any vertical. With this assumption, and applying Darcy's law to small elements of length, we obtain the following general differential equation for the non-steady flow in the aquifer

$$\partial z/\partial t = p + (c/2\epsilon)\,\partial^2 z^2/\partial x^2 = p + (c/\epsilon)\,[z\,\partial^2 z/\partial x^2 + (\partial z/\partial x)^2] \quad \ldots\ldots\ldots (1)$$

It is worth emphasizing that the symbol p denotes the "speed" of the replenishment to the water table (rate of recharge or draft within the soil), and must not be confused with the precipitation. The symbol ϵ denotes that part of the porosity which is interconnected and open to replenishment, and may thus at least approximately be taken equal to the so-called specific yield of the water-bearing material.

If, according to the presumption made in the Introduction, the depth of the ground-water stream is great, and the fluctuations as well as the rate of replenishment is small, we may infer for all practical purposes that the gradient is very small and that z deviates only a moderate amount from a weighted mean depth of the ground-water stream. Eq. (1) then reduces to

$$\partial z/\partial t = p + k\,\partial^2 z/\partial x^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

in which the so-called viscosity factor

$$k = cH/\epsilon \quad \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

The viscosity factor has the same dimension (m^2/sec) = L^2/T) as the kinematic viscosity, hence the denomination. It plays an important role in non-steady ground-water flow. Although differently composed, it appears also in artesian flow [WERNER, 1946, p. 691].

Steady flow--The ground-water level z_s during steady flow due to a constant rate of replenishment p_s is obtained by putting $p = p_s$ and $\partial z/\partial t = 0$ in (1) and integrating, thus

$$z_s = h_s \sqrt{1 + (p_s H/K h_s^2)(L^2 - x^2)} \quad \ldots\ldots (4)$$

in which h_s denotes a constant tail water level. Now it is evident that the expression (4) does not satisfy (2). Provided, however, in accordance with the presumption, that

$$p_s L^2/k h_s << 1 \quad \ldots\ldots (5)$$

we may reduce (4) as follows, without materially affecting its validity for the present problem.

$$z_s = h_s + (p_s/2k)(L^2 - x^2) \quad \ldots\ldots (6)$$

which obviously satisfies (2). The following study of progressive waves will be based on the differential equation (2), with the steady-flow condition represented by (6).

Ground-water discharge--For the flow through the aquifer at the point x and the time t we have

$$q_x = -cz\,\partial z/\partial x \quad \ldots\ldots (7)$$

and thus for the discharge through the outlet section

$$q = -c\,[z\,\partial z/\partial x]_{x=L} \quad \ldots\ldots (8)$$

The discharge under steady-flow conditions is obtained by introducing the expression (6) in (8), thus

$$q_s = c h_s p_s L/k \quad \ldots\ldots (9)$$

Applications

Harmonic fluctuations in tail water level--Assuming that the fluctuations be given by the function

$$h = h_s + a \sin \theta t \quad \ldots\ldots (10)$$

and assuming, further, that the rate of replenishment corresponds to a constant value p_s, the boundary conditions may be written

$$p = p_s \quad \ldots\ldots (11a)$$

$$\partial z/\partial x\big|_{x=0} = 0 \quad \ldots\ldots (11b)$$

$$z\big|_{x=L} = h_s + a \sin \theta t \quad \ldots\ldots (11c)$$

The solution may be taken as the real part of the expression

$$z = z_s - a i e^{i\theta t}[\cosh (1 + i)\beta x/\cosh (1 + i)\beta L] \quad \ldots\ldots (12)$$

which, as may be verified through substitution, satisfies the boundary conditions (11) as well as differential equation (2), provided that $p = p_s$, and that

$$\beta = \sqrt{\theta/2k} \quad \ldots\ldots (13)$$

The real part of (12) is obtained by transformation, thus

$$z = z_s + (a/4)(A + B + C + D)/(\sinh^2 \beta L + \cos^2 \beta L) \quad \ldots\ldots (14)$$

in which

$$A = e^{\beta(L+x)} \sin [\theta t - \beta(L - x)] \quad \ldots\ldots (15a)$$

$$B = e^{-\beta(L-x)} \sin[\theta t + \beta(L+x)] \quad \ldots\ldots\ldots\ldots\ldots\ldots (15b)$$

$$C = e^{\beta(L-x)} \sin[\theta t - \beta(L+x)] \quad \ldots\ldots\ldots\ldots\ldots\ldots (15c)$$

$$D = e^{-\beta(L+x)} \sin[\theta t + \beta(L-x)] \quad \ldots\ldots\ldots\ldots\ldots\ldots (15d)$$

It is realized that the non-steady flow under consideration is to a large extent governed by the value of the dimensionless quantity βL. Excepting very small lengths of the aquifer (see above), (14) is valid for any value of βL. For large values of βL the functions B, C, and D become small in comparison with A, and (14) is then simplified to approximately

$$z = z_s + a e^{-\beta(L-x)} \sin[\theta t - \beta(L-x)] \quad \ldots\ldots\ldots\ldots\ldots\ldots (16)$$

In principle, (16) is of the same form as the corresponding equation for an artesian aquifer [WERNER, 1946, p. 693]. It is seen that the oscillations according to (16) travel inwards from the outlet section with a velocity of propagation of θ/β and a wave-length of $2\pi/\beta$. The amplitude diminishes very rapidly, the decrease within a wave-length being in the proportion $e^{-2\pi}$ or 1/535.

The linear magnitude of $1/\beta$ is of great importance in oscillatory ground-water motions when βL is large. The value $\rho = \mu/\beta$ in which μ is a moderate number, say $\mu = 4$, indicates the extent to which the viscosity effect penetrates into the ground-water stream. Applying (13), we obtain for non-artesian flow,

$$\rho = \mu\sqrt{2cH/\epsilon\theta} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (17)$$

It is seen that the ρ-value increases with increasing permeability and depth of the aquifer and increasing length of period, but decreases with increasing porosity of the aquifer. In the case just treated, see (16), the influence of the tail water fluctuations is practically nil for $L - x > \rho$, where ρ is taken from (17), with $\mu = 4$.

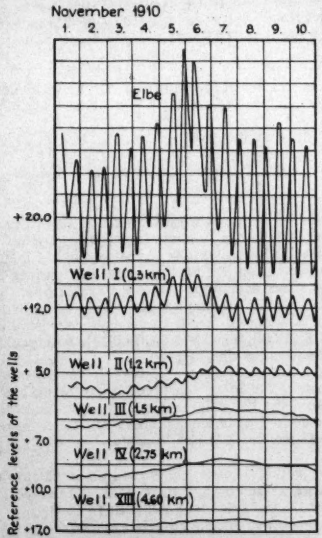


Fig. 3--Ground-water fluctuations in the banks of the River Elbe [according to E. PRINZ, 1923] (km values are distances from river)

Figure 3, which is reproduced from a work by PRINZ [1923, p. 100] furnishes a good illustration of (17) with respect to the period. It shows the progressive ground-water waves in the banks of the River Elbe caused by two different motive fluctuations, one semidiurnal and the other having a period of some nine days. The proportion between the square roots of these periods is about 1/4, which value satisfactorily agrees with the actual observations of the extinction of the ground-water fluctuations.

Harmonic fluctuations in replenishment--A very important question geophysically is how the non-artesian ground-water stream behaves, in principle, when the rate of replenishment is subject to daily and seasonal, or similar, fluctuations. It should be observed that the motive fluctuation is here constituted by the replenishment, not by the rainfall. Between the rainfall and the replenishment there lies the process of vertical percolation, the physical mechanism of which, however, does not fall within the scope of the present study.

Let the motive fluctuation be given by the function

$$p = p_s + b \cos \theta t \ldots\ldots\ldots (18a)$$

implying that the harmonic fluctuation is superimposed on the steady-flow value p_s. The remaining boundary conditions are

$$\partial z/\partial x\big|_{x=0} = 0 \ldots\ldots\ldots (18b)$$

$$z\Big|_{x=L} \cong h_s \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (18c)$$

Differential equation (2) in this case takes the form

$$\partial z/\partial t = p_s + b \cos \theta t + k\, \partial^2 z/\partial x^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (19)$$

It is easily verified through substitution that the solution is obtained by taking the real part of the expression

$$z = z_s - (ibe^{i\theta t}/\theta)\,[1 - \cosh (1 + i)\beta x/\cosh (1 + i)\beta L] \quad \ldots\ldots\ldots\ldots \quad (20)$$

After transformation, (20) becomes

$$z = z_s + (b/\theta)\,[\sin \theta t - (A + B + C + D)/4\,(\sinh^2 \beta L + \cos^2 \beta L)] \quad \ldots\ldots\ldots \quad (21)$$

in which β is given by (13) and the functions A, B, C, and D by (15).

For large values of βL, (21) approximately reduces to

$$z = z_s + (b/\theta)\left\{\sin \theta t - e^{-\beta(L-x)} \sin [\theta t - \beta (L - x)]\right\} \quad \ldots\ldots\ldots\ldots \quad (22)$$

This formula shows that the ground-water fluctuations, quite naturally, are zero at the outlet and tend to regularly increase towards the ground-water divide. However, for sections located at a distance from the outlet section greater than the ρ-value as defined by (17), that is, $L - x > \rho$ (25) is simplified approximately to

$$z = z_s + (b/\theta) \sin \theta t \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (23)$$

It appears from (23) that, when βL is large, the main body of the non-artesian ground-water stream is subject to what may be denominated "free" oscillations. Moreover, these oscillations are a quarter-period out of phase relative to the replenishment, that is, the same time lag as would occur in a non-overflow basin. The amplitude of the oscillations according to (23) is b/θ. Experience, and observations in nature [McGUINESS, 1946; PRINZ, 1923, p. 101], indicate that the amplitude is ordinarily rather small.

As regards the discharge of the aquifer, it is obtained, for large values of βL, by introducing (22) in (8), thus

$$q = ch_s\,[p_s L/k + (b\beta\sqrt{2}/\theta) \cos \theta\,(t - T/8)] \quad \ldots\ldots\ldots\ldots\ldots \quad (24)$$

which shows that the discharge is one-eighth of a period out of phase relative to the replenishment.

It is, of course, no easy matter to procure a general quantitative confirmation of the above results because of the many obscuring influences met with in nature, such as frost, intermittent visible storage, superposition of different fluctuations, and irregularities in the aquifer. A qualitative confirmation, however, is readily obtained, as the general trend of seasonal fluctuations is traceable in many streams. Probably the most conspicuous demonstration of the problem is found in the study of transpiration through vegetation, which is known to cause very marked daily and seasonal fluctuations in a water table. Reference may here be made to the comprehensive investigations performed by WHITE [1932], BARKSDALE [1933], and TROXELL [1936], which contain numerous examples of observed short-term fluctuations of this nature.

Figure 4 shows some typical ground-water records of the Santa Ana River in California, as reproduced from TROXELL [1936]. The curve A represents the water-table fluctuations in a well called E-1, which is of particular interest in this connection. It is located some 1,000 ft from the river, most certainly outside the ρ-value of the aquifer, so that (23) should apply.

Figure 1 demonstrates some detail records of the well E-1, covering the variations during two days of the following items, namely, A the discharge of the river, B the ground-water level, and C the temperature. According to investigations by C. A. Taylor [see TROXELL, 1936, pp. 499-500], it may be assumed that transpiration from vegetation agrees closely with the temperature, other influencing factors, such as humidity and wind, being equal. For the short period in the special case under consideration we take it, like Troxell, that the temperature constitutes the sole

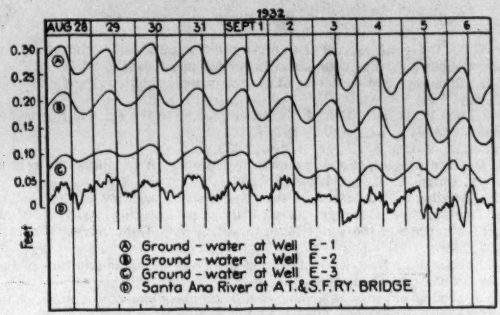


Fig. 4--Typical ground-water record, Santa Ana River [according to TROXELL, 1936]

agent. The curve C in Figure 1 would then, to a certain scale, represent the motive fluctuation. Having this in mind, and allowing for the fact that the motive fluctuation is not truly harmonic, the observations seemingly furnish a quite satisfactory verification of the present theory. This, maybe, applies especially to the relative location of the peaks and troughs of curves C and B, representing, in turn, the motive fluctuation and the ground-water level, which closely agrees with the theoretical results as expressed by (18a) and (23). Curve A in Figure 1 cannot be readily interpreted in this connection, but Figure 4 seems to clearly indicate also the validity of the time lag for the discharge as expressed by (24) relative to (23).

The ground-water levels shown in Figures 1 and 4 have a steady downward trend. This, of course, indicates either that the ground-water stream is subject to a continuous draft or that the fluctuations considered are superimposed on some fluctuations of longer period.

In the foregoing it has been demonstrated theoretically and, so far, been substantiated by actual measurements that, when βL is large, the ground-water fluctuations are a quarter-period out of phase relative to the motive fluctuation. Now it is known [PRINZ, 1923, pp. 97-101; VEATCH, 1906, pp. 29-52] through observations in nature that the time lag between rainfall and ground-water fluctuations may vary considerably for different aquifers and may even be practically non-existent. This phenomenon is, of course, to some extent related to the lag caused by the percolation process, but part of it may no doubt be attributed to the horizontal transmission capacity of the aquifer, inherent in the general solution as given by (21). Let us again consider this formula. For small values of βL, which, of course, does not necessarily imply a very small length of the ground-water stream, (21) reduces approximately to

$$z = z_s + (b/2k)(L^2 - x^2)\cos\theta t \quad \ldots\ldots\ldots\ldots\ldots\ldots (25)$$

showing that in this case the ground-water fluctuations are in phase with the motive fluctuation. Now there must evidently exist a transition between the two limiting cases represented by (23) and (25), as may also be shown through a general examination of (21). In principle, the peculiar time-lag variation considered here naturally applies also to the ground-water discharge.

The point just discussed presents interesting aspects relating to the hydrology of non-artesian aquifers. Indeed it seems to enable a rational approach to the interpretation of certain rather important phenomena in ground-water flow under water-table conditions. Lately, the validity of such concepts as quick return flow and concealed surface runoff has been seriously questioned by ROESSEL [1950], who postulates that the length of the aquifer is a governing factor in the natural control of ground-water storage. However, according to the theory presented above, it is not the length itself, but the dimensionless quantity βL that largely determines the sensitiveness of the aquifer to variations in replenishment and thus, aside from the vertical percolation process, also in rainfall. It may be noted that the βL-value is directly proportional to the length of the aquifer and inversely proportional to the square root of the viscosity factor.

References

BARKSDALE, H. C., A ten-year record of water-table fluctuations near Runyon, New Jersey, Trans. Amer. Geophys. Union, 14th annual meeting, pp. 466-471, 1933.

McGUINESS, C. L., Recharge and depletion of ground-water supplies, Proc. Amer. Soc. Civ. Engr., v. 72, Sep. 1946.

McDONALD, C. C., and W. B. LANGBEIN, Trends in runoff in the Pacific Northwest, Trans. Amer. Geophys. Union, v. 29, pp. 387-397, 1948.

PRINZ, E., Hydrologie, Verlag Springer, Berlin, 1923.

ROESSEL, B. W. P., Hydrologic problems concerning the runoff in headwater regions, Trans. Amer. Geophys. Union, v. 31, pp. 431-442, 1950.

TROXELL, H. C., The diurnal fluctuation in the ground water and flow of the Santa Ana River and its meaning, Trans. Amer. Geophys. Union, 17th annual meeting, pp. 496-504, 1936.

VEATCH, A. C., Fluctuations of the water level in wells, U. S. Geol. Survey Water-Supply Paper 155, pp. 28-52, 1906.

WERNER, P. WILH., Notes on flow-time effects in the great artesian aquifers of the Earth, Trans. Amer. Geophys. Union, v. 27, pp. 687-708, 1946.

WHITE, W. N., A method of estimating ground-water supplies based on discharge by plants and evaporation from soil, U. S. Geol. Survey Water-Supply Paper 659A, 1932.

A. B. Vattenbyggnadsbyrån,
Humlegårdsgatan 29,
Stockholm, Sweden

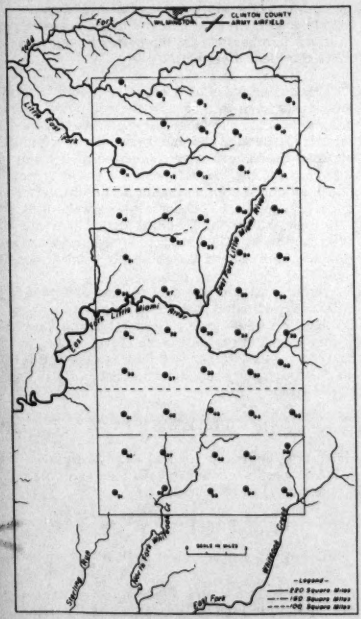
(Communicated manuscript received October 16, 1950;
open for formal discussion until September 1, 1951.)

VARIATIONS IN STORM RAINFALL OVER SMALL AREAS

Ray K. Linsley and Max A. Kohler

Abstract--Variation in rainfall over small areas has been a subject of considerable interest to hydrologists and meteorologists, but, because of inadequate data, little analytical work has been possible. The precipitation-gage network established for the Army-Navy-NACA-Weather Bureau Thunderstorm and the Weather Bureau Cloud Physics Projects near Wilmington, Ohio, included 55 rain gages at approximately two-mile intervals. Utilizing data from this network the authors have analyzed the variations in average precipitation for storms computed from networks of differing densities and the relation between point and areal-average values of rainfall in storms.

Introduction--A great many hydrologic problems require the determination of the average depth or volume of precipitation over an area. It is obviously not possible to measure directly the volume of precipitation falling on a natural basin. The best that can be done is to sample this precipitation in gages scattered about the area and to compute an average by any of several methods. Frequently a subtraction is made from this average to compute a residual as, for example, the subtraction of infiltration to determine runoff. A small error in the computed average precipitation becomes a far larger percentage error in such a residual value. Thus, a knowledge of the possible errors in computed average precipitation is important. Very little work has been done in this direction except that by LANGBEIN [1946] and LIGHT [1947, Chap. 3].


CLINTON COUNTY ARMY AIRFIELD
Fork
Todd Fork
Todd Fork
East Fork Little Miami River
Little Miami River
Little Miami River
Caesar Creek
Caesar Creek
Caesar Creek
Todd Fork
Clear Fork
Clear Fork
Clear

for each storm determined. Analysis of the record disclosed 68 storms varying from 0.01 to 4.65 inches with maximum duration of about 60 hours.

Purpose of study--The analysis described was made to estimate (1) the representativeness of networks of specified density (with stations well distributed areally); (2) the variation in the reliability of a single gage with its distance from the center of the area under consideration; (3) the frequency distribution of the error in assuming a single gage, randomly placed, to represent the average within the 220-square mile area; and (4) the representativeness of a single gage centrally located in areas of various sizes.

One of the first steps in the analysis was to determine whether any persistent areal pattern was detectable, since, if this were the case, some stations would always display relatively high departures from the 55-station mean. It will be noted from Figure 2, a schematic plotting of total recorded precipitation at each station, that no pronounced pattern exists.

Reliability of averages from networks of different density--Presumably the error E of computed average precipitation is a function of the precipitation P, the area A, and the number of precipitation gages N. If an adequate general equation expressing this relationship could be found, the problem of the reliability of precipitation averages would be solved.

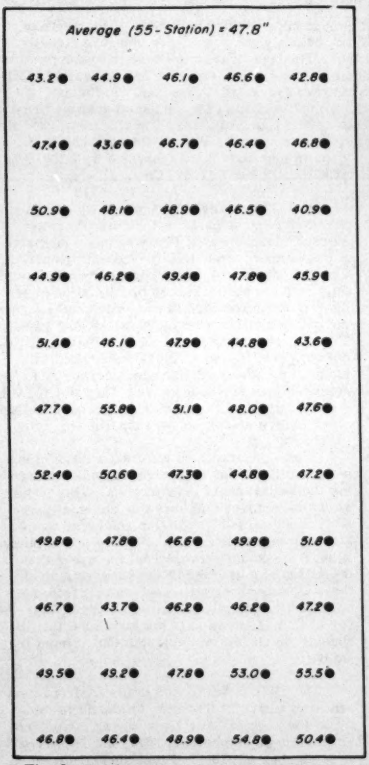


Fig. 2--Total precipitation, Apr. 29-Sep. 21, 1947 and Feb. 5-Sep. 22, 1948 (inches)

To determine the relative reliability of the average rainfall computed from networks of differing density, the average precipitation for networks consisting of 1, 2, 3, 4, 10, 18, and 55 stations was computed for each of the 68 storms. In each case the stations were selected on as nearly a uniform grid pattern as the network permitted. In other words, the networks approximate the ideal distribution.

Using the 55-station mean as a control, the deviations from this base of the computed average rainfall for the other networks were determined. Inspection indicated that the absolute deviations (in inches) were a function of precipitation amount, and the data were therefore grouped into four classes on the basis of the 55-station mean precipitation. These classes were 0.01 to 0.20 inch, 0.21 to 0.50 inch, 0.51 to 1.00 inch, and over 1.00 inch. The average deviations were then computed for each class and each network density.

Examination of the data for the 220-square mile area indicated that an equation of the form $E = KP^nN^m$ would give a good fit. Using least squares analysis to determine K, m, and n, a correlation coefficient of 0.97 was obtained for the following equation (shown graphically in Fig. 3):

$$E_{220} = 0.186P^{0.47}N^{-0.60} \quad \ldots\ldots (1)$$

Similarily, equations for 160 and 100 square miles (correlation coefficients 0.95 and 0.98 respectively) were found to be

$$E_{160} = 0.181P^{0.36}N^{-0.52} \quad \ldots\ldots (2)$$

$$E_{100} = 0.176P^{0.44}N^{-0.78} \quad \ldots\ldots (3)$$

The usual least squares solution for equations of this type minimizes the deviations of the logarithms of the computed values of E. This in

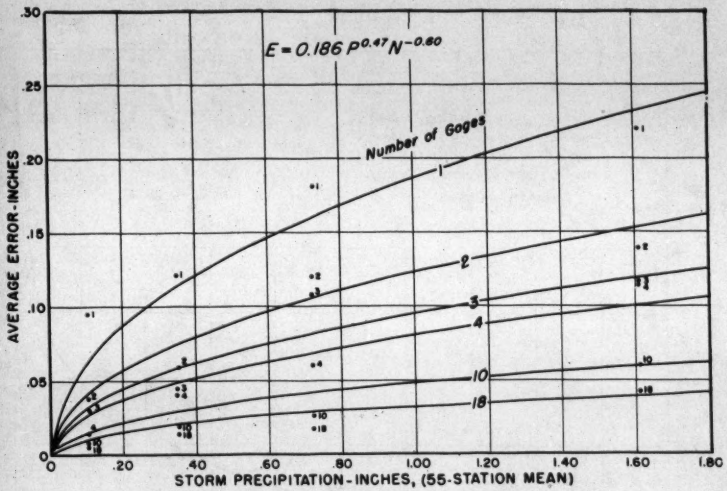


Fig. 3--Relation between storm precipitation, number of gages in 220 sq mi, and the error of computed average precipitation

effect yields an equation with minimum standard error of estimate in terms of percentage. Eq. (1), (2), and (3), however, were derived using the procedure described by EZEKIEL [1941, p. 99] which minimizes the summation of the squares of the absolute deviations $\Sigma(E - E_{comp})^2$.

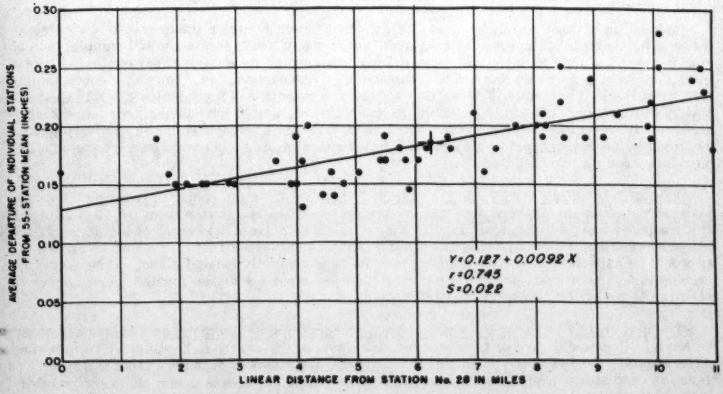


Fig. 4--Relation between the average departure of individual stations from the 55-station mean and their distance from the center of the area

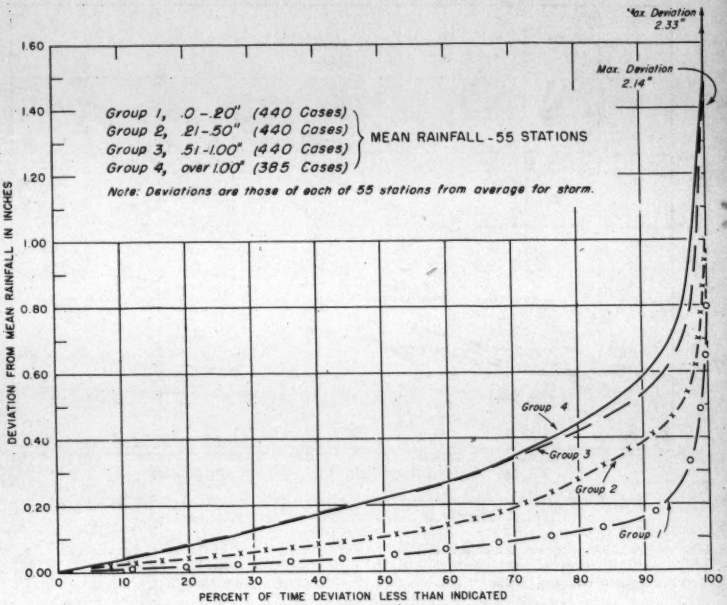


Fig. 5--Frequency distribution of the deviations of individual station amounts from the 55-station mean for storms of various magnitudes

Inspection of these equations shows that the coefficient K varies linearly with area while there is no evident relationship between area and m and n. With such a limited sample, it is obviously impracticable to develop a relation involving area as an additional parameter. Rationalizing, however, E must approach zero when the area approaches zero. Since this condition must hold when P and N are unity, K must also approach zero with A. The function $K = kA^c$ would satisfy this requirement and is probably the most obvious way of introducing area into the relationship. However, m is undoubtedly a function of area and n might also be. The nature of these functions is not obvious and in view of the limited range of area studied no attempt was made to introduce area into the relation.

Variation in reliability of a single gage with distance from the center of the area--For this phase of the study the average departure of precipitation at each station from the 55-station mean was computed and plotted against the distance of the station from the center of the area (Station 28). The resulting relation, which has a correlation coefficient of 0.745, is shown in Figure 4. As would be expected, the relation shows that the gage centrally located gives, on the average, the best measure of areal precipitation. Note that the error for a gage located at one corner of this area is nearly twice that of the center gage.

The distribution of error for a single gage randomly located in the area--As another phase of the study, it seemed desirable to determine something of the errors to be expected from a single gage randomly located in the basin. Accordingly the deviations of each gage from the 55-station mean for each storm (Apr. 29 to Sep. 21, 1947) was computed. These deviations were grouped into the four precipitation classes previously mentioned and the data then assembled in order of magnitude within each class for a frequency distribution (see Fig. 5). As would be expected, the magnitude of the deviations increases with increasing precipitation although the difference between the two larger classes is very small.

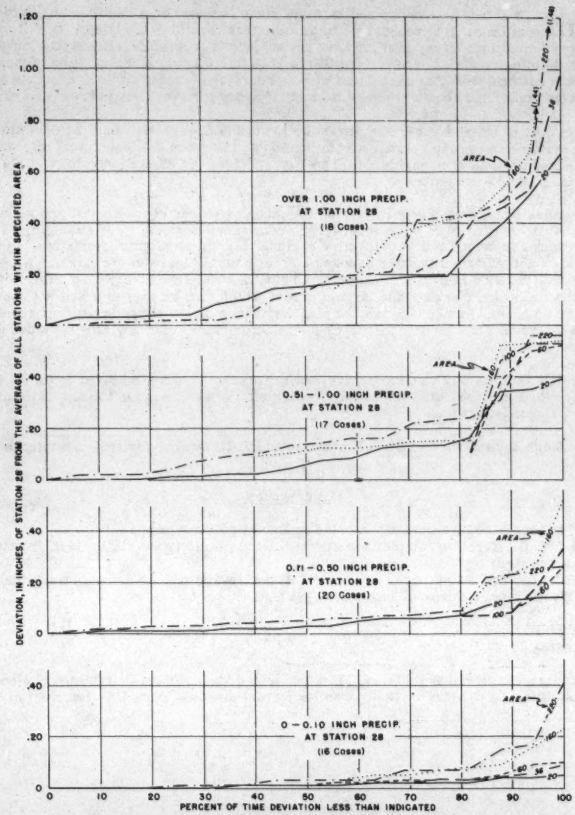

OVER 1.00 INCH PRECIP.
AT STATION 28
(18 Cases)
0.51 – 1.00 INCH PRECIP.
AT STATION 28
(17 Cases)
0.11 – 0.50 INCH PRECIP.
AT STATION 28
(20 Cases)
0 – 0.10 INCH PRECIP.
AT STATION 28
(16 Cases)
AREA
DEVIATION, IN INCHES, OF STATION 28 FROM THE AVERAGE OF ALL STATIONS WITHIN SPECIFIED AREA
PERCENT OF TIME DEVIATION LESS THAN INDICATED

Fig. 6--Frequency distributions of deviations of storm precipitation at Station 28 from the average of all stations within areas of various sizes

The distribution of error for a single gage centrally located in areas of various sizes--A question often encountered in consideration of network adequacy is, "What magnitude of errors can be expected when a single gage is assumed to represent some specified area?" Although an immense amount of data would be required to provide a reliable answer to this question, the available data were analyzed for what value they may have in serving as a guide. Figure 6 shows the results of this analysis in terms of error-frequency distribution for various areas and classes of precipitation. In this case the "errors" are the differences between the precipitation at Station 28 and the average of all stations within areas of various sizes centered about Station 28. As before the data have been grouped on the basis of precipitation classes but in this case using Station 28 as a base. Based on limited data, the figure indicates that there is little correlation between error and area, except for the larger and less frequent errors.

Summary--It should be emphasized that this study is based on a limited sample for a single locality in central Ohio. It is reasonable to assume that results would be not far different for thunderstorm conditions in any similar area not subject to orographic effects (the range in elevation in the Wilmington area is from about 950 to 1100 ft). The areal distribution of general frontal rain is more uniform than that associated with thunderstorms and a network adequate under thunderstorm conditions should be more than satisfactory for measuring general rains.

As a matter of interest a cursory investigation of the data showed that the deviations both of individual stations and group averages from the 55-station mean decrease markedly when averages for longer periods are considered. Ten-day averages for 27 stations differ at the most only 0.02 inch from the 55-station mean.

The studies summarized above disclose the fact that extremely dense networks are not required if the occurrence of an occasional large error is not serious. For example, a relatively sparse network can be utilized to determine regional precipitation characteristics. In some problems it is not sufficient that the errors be usually small but even the extreme errors must be kept within specified tolerances. Reporting networks for river forecasting should be of sufficient density to assure that even the largest errors which may be expected will not cause a gross error in the forecast. In other words, the planning of a multiple-purpose network requires consideration of an acceptable error frequency distribution rather than any single-valued criterion of accuracy.

This study is in no way comprehensive, but represents only a simplified approach intended to answer specific questions. It is hoped that further efforts will be made to study this important problem on a broader scale.

The authors are indebted to T. J. Nordenson and J. D. Brewer for their assistance in carrying out the study.

References

EZEKIEL, M., Methods of correlation analysis, 2nd ed., John Wiley, 1941.

LANGBEIN, W. B., Error in computation of mean areal precipitation, U. S. Geol. Survey, Aug. 1946 (processed).

LIGHT, PHILLIP, The reliability of areal rainfall determinations, Hydrometeorological Rep. 5, U. S. Weather Bur.-Corps of Engineers, 1947.

U. S. Weather Bureau,
Washington 25, D. C.

(Manuscript received October 19, 1950; presented at the Thirty-First Annual Meeting, Washington, D. C., May 1, 1950; open for formal discussion until September 1, 1951.)

Transactions, American Geophysical Union Volume 32, Number 2 April 1951

THE CHEMICAL POTENTIAL OF A STRESSED SOLID

J. Verhoogen

Abstract--The distribution of the chemical potential in a non-hydrostatically stressed solid has been investigated. It is shown that in strained elastic bodies the potential must have the same value at all points in the solid; and a simple expression relating the chemical potential to the components of stress is derived. The effect of pure shear on the chemical equilibrium of elastic bodies appears to be small. For non-elastic bodies which have not reached a stable configuration under stress there is an additional term in the chemical potential which is a continuous function of position in the body. The numerical value of this term cannot be computed without making additional assumptions concerning the mechanism of deformation or flow; but it appears to be small, at least for nearly elastic bodies. Elastic anisotropy is probably not an important factor in the development of an oriented fabric in rocks. Such recrystallization as may be caused by non-hydrostatic (shear) stress is believed to result mostly from an initially uneven distribution of the stresses in the grains of the rock, or from the effect of shear on the rates of certain reactions.

Introduction--The purpose of this paper is to clarify the behavior, with respect to chemical equilibrium, of solids under non-hydrostatic stress. The matter is of considerable importance to geologists, as it has been argued that non-hydrostatic stress (shear) plays an important role in the mineralogical reconstitution of metamorphic rocks, as in the development of schistosity by "growth of crystals normally to the greatest pressure with the production of elongated forms oriented parallel to the direction of least pressure" [TYRRELL, 1926, p. 266], or in the development of "stress" minerals believed to be incapable of forming in the absence of shear. Another possible effect of non-hydrostatic stress may be the disappearance of "antistress" minerals which are believed to become unstable under such conditions [TURNER, 1948, pp. 30-31].

As the behavior of a substance with respect to physico-chemical processes is adequately described by its chemical potential, we shall be concerned essentially with the relations that may exist between the stresses and the distribution of the chemical potential in the body. The chemical potential or, for short, the potential of a substance, is defined in a system under hydrostatic pressure P by any one of the equivalent relations

$$\mu_i = (\partial E/\partial n_i)_{S,V,n_j} = (\partial H/\partial n_i)_{S,P,n_j} = (\partial F/\partial n_i)_{T,V,n_j} = (\partial G/\partial n_i)_{P,T,n_j} \quad \ldots\ldots (1)$$

where E, H, F, G are respectively the internal energy, enthalpy, Helmholtz free energy and Gibbs free energy; S is entropy, V is molar volume, T is temperature, n_i is the number of moles of component i, and n_j is the number of moles of any component except i. We have further

$$G = \sum_i n_i \mu_i \quad \ldots\ldots (2)$$

The dependence of the chemical potential on hydrostatic pressure is given by

$$(\partial \mu_i/\partial P)_{T,n_j} = v_i \quad \ldots\ldots (3)$$

where v_i is the partial molar volume of i. The chemical potential of a component i of a solution is related to its activity a_i in this solution by the well-known relation

$$\mu_i = \text{constant} + RT \log_e a_i \quad \ldots\ldots (4)$$

the value of the constant depending on temperature and pressure, but not on composition. For an ideal solution the activity of i is equal to the mole fraction of i in this solution.

Unless otherwise specified, it will be assumed in this paper that the state of stress is homogeneous; that is, the components of stress have the same value at all points in the body. Failure to recognize clearly the difference between a homogeneous non-hydrostatic stress and a hetero-

geneous one (hydrostatic or not) has led to many ambiguous or erroneous statements to be found in geologic literature. A heterogeneous hydrostatic stress may exist, for instance, in a fluid at rest in a gravitational field, since the pressure is everywhere hydrostatic but does not have the same value at different levels.

Equilibrium of stressed solids--The conditions for mechanical and chemical equilibrium between a stressed solid and a fluid in contact with it were first investigated by GIBBS [1906, p. 196]. Gibbs considered only the cases in which (a) the total entropy is constant, that is, all processes are reversible and no heat is added to or subtracted from the system; and (b) the total volume is constant, that is, any change in volume in the fluid resulting from crystallization or solution of the substance of the solid must be compensated by changes in volume of the solid resulting either from changes in strain or from solution or accretion. Under these conditions the internal energy must be minimum, which leads to the condition, in Gibbs' own notations (his eq. 388)

$$\epsilon - t\eta + pv = m\mu \qquad (5)$$

where ϵ, η, v, and m are respectively the internal energy, entropy, volume, and mass of the solid in the strained state and μ is the chemical potential (per unit mass) of the substance of the solid in the fluid; p is the (hydrostatic) pressure prevailing in the fluid in mechanical equilibrium with the solid over the portion of the surface of the solid where they come into contact. Gibbs considered further the case of a solid bounded by six faces perpendicular in pairs to the principal axes of stress and in contact with fluids on all these faces. Obviously, if the solid is to be under non-hydrostatic stress these three fluids must be under different pressures p', p'', p''', equal respectively to the three principal tractions taken negatively. Chemical equilibrium with respect to the tendency of the solid to dissolve in any of these fluids requires then that we have simultaneously

$$\left.\begin{aligned} \epsilon - t\eta + p'v &= m\mu' \\ \epsilon - t\eta + p''v &= m\mu'' \\ \epsilon - t\eta + p'''v &= m\mu''' \end{aligned}\right\} \qquad (6)$$

Gibbs showed further that "the fluids in contact with the solids are all supersaturated with respect to the substance of the solid, except when the solid is in a state of hydrostatic stress; so that if there were present in any one of these fluids any small fragment of the same kind of solid under the hydrostatic pressure of the fluid, such a fragment would tend to increase." The stressed solid is thus pictured as being metastable with respect to the same substance under the hydrostatic pressure of any one of the fluids; and it must be noted in addition that when the conditions of (6) are satisfied, the three fluids are not in mutual equilibrium with respect to the substance of the solid. For if these fluids were separated by rigid membranes permeable to the substance of the solid, there would be diffusion of this substance towards the fluid at the lowest pressure.

A few years later RIECKE [1895] computed the depression ΔT of the melting point of a solid under a uniform linear compression C, the two other principal stresses being 0. Assuming elastic behavior, he obtained the result

$$\Delta T = TC^2/2\rho_0 E_y Q \qquad (7)$$

where ρ_0 is the density of the solid in the unstressed state, T is the absolute temperature of melting of the unstressed body, Q is the latent heat of melting, and E_y is Young's modulus. Riecke pointed out that if two prisms of the same solid are originally in equilibrium with the same saturated solution, application of stress to one of the prisms would cause it to go into solution while the unstressed prism would grow at its expense. Riecke made no mention of this tendency to go into solution being greater on certain faces than on others, or of a tendency towards simultaneous solution and deposition on different faces, although his "principle" has often been stated as implying such an effect.

The effects of mechanical stresses on equilibrium between a solid and a liquid, as in the case of melting, were further investigated by BRIDGMAN [1916] and WILLIAMSON [1917]. Williamson considered particularly, as Riecke had done, the case of a solid under uniform compression and obtained for the depression of the melting point at a free surface an expression which is identical with that derived by Riecke. At a stressed surface, on the contrary, the depression of the melting point is independent of the elastic moduli of the substance.

GORANSON [1930] gave a more general treatment of the subject in which he defined the Gibbs free energy per unit mass of the stressed body by the relation

$$G = E - TS - (1/\rho_0) \sum_1 e_i X_i \quad (i = 1, 2, \ldots 6) \quad \ldots\ldots\ldots\ldots\ldots\ldots (8)$$

where E is the internal energy; S, the entropy; and ρ_0, the density in the reference state. $X_1 \ldots X_6$ are the components of stress and $e_1 \ldots e_6$ are the components of strain. Eq. (8) also appears in an article by RICE [1936]. Using this definition of G, GORANSON [1940] later stated that for a elastic body under simple tension or compression of magnitude X, the change in activity a would be given by the relations

At a stressed face $\quad d(\log_e a)/dX = M/RT\rho \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9a)$

At a free face $\quad d(\log_e a)/dX = MX/\rho RT E_y \ldots\ldots\ldots\ldots\ldots\ldots\ldots (9b)$

where M is the molar mass, R is the usual gas constant, and E_y is Young's modulus. These relations imply that the chemical potential of the solid will be different in solutions in contact with stressed or free faces.

Goranson's treatment appears to lead to some difficulties. For instance, his definition of G does not reduce to the usual definition in case of hydrostatic pressure

$$G = E - TS + PV \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (10)$$

Indeed, in such a case $X_1 = X_2 = X_3 = -P$; $e_1 = e_2 = e_3 = (V - V_0)/3\,V_0$; $V_0 = M/\rho_0$ being the molar volume in the state of reference. All other stress and strain components are 0. Eq. (8) then becomes $G = E - TS + P(V - V_0)$, which differs from (10) by the variable term PV_0. Furthermore, (8) suggests that the free energy is a function of the magnitude of the strains; for instance, the free energy of a completely undeformable body, if such existed, would be independent of stress. By (3), the change of free energy at constant temperature for a pure substance under hydrostatic pressure is

$$dG = VdP \qquad (11)$$

which remains valid whether the body be deformable or not.

If the chemical potential varies from face to face in the stressed body, this body is not in a stable state of equilibrium, for there will be a tendency for transfer of matter by internal diffusion, or by external diffusion through the fluids in contact with the solid. One would then expect that, granting sufficient time, the body would deform by flow or internal diffusion until it assumes a shape such as to make the stresses hydrostatic, and establish a uniform distribution of the potential. Such a body would not be elastic in the usual sense of a body for which the strain under given stress is independent of time, or of one in which the stress-strain relationships are perfectly reversible; for flow or diffusion are essentially irreversible processes and are therefore inconsistent with the existence of the strain-energy function as defined in elasticity.

It appears necessary therefore to make a sharp distinction between elastic bodies in which all processes of stressing and straining are reversible, and non-elastic bodies in which application of stress may lead to irreversible phenomena. We shall first consider the former.

Elastic bodies--An essential assumption of the theory of elasticity is that a body acquires under stress a state of strain such that the forces at any point inside the body will balance. These forces may be either body forces or forces resulting from external constraints applied over the surface of the body. Similarly, we shall assume that the state of strain is precisely such that the chemical potential becomes uniform throughout the body. This assumption is in fact equivalent to the usual statement that the strain-stress relationships are reversible. We consider thus that at the moment the stresses are applied, the internal equilibrium is disrupted; the body then deforms in such a manner as to restore equilibrium between all its parts. This readjustment is assumed to occur instantaneously in elastic bodies, so that the initial, non-equilibrium distribution of the potential is of no practical importance. This, however, is not true for non-elastic bodies in which the stable configuration may be reached only after considerable time or may never be reached at all, as in fluids which deform continuously as long as the stresses are applied.

To find the dependence of the chemical potential on stress we follow the classical procedure for finding its dependence on any intensive variable. The body is considered to be isotropic, and

the strains are small. We consider as usual that the internal energy E is a function of volume, entropy, and number of moles of each component; but E must also be a function of some variable A representing the distortion of the body; otherwise shearing stresses resulting in a change in shape but not in volume would not be properly taken into account. We write thus $E = E(S, V, A, n_i)$. Differentiating

$$dE = (\partial E/\partial S)_{V,A,n_i}\, dS + (\partial E/\partial V)_{S,A,n_i}\, dV + (\partial E/\partial A)_{S,V,n_i}\, dA + \sum_i (\partial E/\partial n_i)_{S,V,A,n_j}\, dn_i \quad (12)$$

If the body is strained reversibly we have for a system of constant composition

$$dE = dQ + dW = TdS + dW \quad (13)$$

dW being the work done on the system (which reduces to -PdV in the case of hydrostatic pressure). More generally, if there is also a variation in the number of moles of the components, according to (1) we shall have

$$dE = TdS + dW + \sum_i \mu_i\, dn_i \quad (14)$$

Let X_1, X_2, X_3 and e_1, e_2, e_3 be respectively the principal stresses and strains. The principal strains e_1, e_2, e_3 are such that a rectangular parallelliped with edges of length (l_1, l_2, l_3) parallel to the principal directions of stress becomes after deformation a similar rectangular paralleliped with edges of length $l_1(1 + e_1), l_2(1 + e_2), l_3(1 + e_3)$. It is convenient to introduce these quantities under invariant forms which will make our results independent of any particular choice of axes. We define thus the two quantities

$$-P = (X_1 + X_2 + X_3)/3 \quad (15)$$

and

$$X = [(X_1 - X_2)^2 + (X_2 - X_3)^2 + (X_3 - X_1)^2]^{1/2}/3 \quad (16)$$

P, the "mean pressure", has all characteristics of a hydrostatic pressure. X is the "octahedral shearing stress", that is, the shear acting in an "octahedral" plane intersecting the three principal axes at equal distances from the origin, P being the stress normal to such a plane. It will be noticed that X reduces to 0 for a hydrostatic stress, $X_1 = X_2 = X_3$. Similarly, we introduce the strain invariants

$$\theta = e_1 + e_2 + e_3 \quad (17)$$

and

$$A = [(e_1 - e_2)^2 + (e_2 - e_3)^2 + (e_3 - e_1)^2]^{1/2} \quad (18)$$

where θ is the cubical dilatation and A the octahedral shear.

If λ and μ are the usual Lame's coefficients (μ, the rigidity, is not to be confused with the chemical potential) we have further

$$-3P = (3\lambda + 2\mu)\,\theta \quad (19)$$

and

$$2\mu = (X_1 - X_2)/(e_1 - e_2) = (X_2 - X_3)/(e_2 - e_3) = (X_3 - X_1)/(e_3 - e_1) = 3X/A \quad (20)$$

The work per unit volume w done by the external forces acting from the unstrained state to the state of equilibrium may be written in the form [SOKOLNIKOFF, 1946, p. 90, Eq. (26.11) and (26.12)]

$$w = (\lambda + 2\mu)\,\theta^2 - 4\mu\theta_2 \quad (21)$$

where w is defined as the work of the forces, not the potential energy of deformation, and θ_2 is the strain invariant $e_1e_2 + e_2e_3 + e_3e_1$. From (17) and (18), and (19) and (20), multiplying by the total volume V_0, we obtain for the total work W done on the system

$$W = -PV_0\theta + V_0AX \quad (22)$$

Differentiating at constant stress, and remembering that $\theta = (V - V_0)/V_0$ we have

$$dW = -P\, dV + X\, V_0\, dA \quad (23)$$

which reduces to the classical form for hydrostatic stress ($\bar{X} = 0$). Then by (14) we have

$$dE = TdS - PdV + XV_o\, dA + \sum_i \mu_i\, dn_i \quad \ldots\ldots\ldots\ldots\ldots\ldots (24)$$

and comparison with (12) shows that we must have

$$(\partial E/\partial S)_{V,A,n_i} = T \qquad (\partial E/\partial V)_{S,A,n_i} = -P \qquad (\partial E/\partial A)_{S,V,n_i} = XV_o \qquad (\partial E/\partial n_i)_{S,V,A,n_j} = \mu_i \quad (25)$$

We proceed now to define G in such a way that (a) it reduces to (10) for hydrostatic stress; (b) the free energy change for a reversible process occurring at constant composition, temperature, and stress should be 0; and (c) $G = \sum_i n_i \mu_i$ as in (2). The function

$$G = E + PV - XV_oA - TS \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (26)$$

satisfies these requirements. Indeed, for $A = 0$ or $X = 0$ it reduces to (10). Differentiating and combining with (24) we get

$$dG = V\, dP - S\, dT - V_o\, A\, dX + \sum_i \mu_i\, dn_i \quad \ldots\ldots\ldots\ldots\ldots\ldots (27)$$

which, by integration for constant values of the intensity factors, leads to

$$G = \sum_i \mu_i n_i \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (28)$$

Differentiating and comparing with (27) shows that

$$-V\, dP + S\, dT + V_oA\, dX + \sum_i n_i\, d\mu_i = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots (29)$$

which is a generalized Gibbs-Duhem relation. In particular, for a system consisting of a single pure component, we have

$$(\partial \mu_i/\partial P)_{T,X} = V \qquad (\partial \mu_i/\partial T)_{P,X} = -S \qquad (\partial \mu_i/\partial X)_{P,T} = -V_oA \quad \ldots\ldots\ldots (30)$$

from which we obtain the variation of the chemical potential as a function of stress defined by the two invariants (15) and (16).

To illustrate the use of these relations, let us consider two simple examples of stress at constant temperature.

Simple compression--Assume a state of stress defined by $X_1 = X_2 = 0$, $X_3 = -C$. Then $P = C/3$, $dP = dC/3$, $X = \sqrt{2}\, C/3$, $dX = (\sqrt{2}/3)\, dC$. The principal strains are $e_1 = e_2 = -\sigma e_3$, $e_3 = -C/E_y$, σ being Poisson's ratio and E_y Young's modulus. Then $A = -\sqrt{2}\, C(1 + \sigma)/E_y$. The variation of the chemical potential at constant temperature and composition is

$$d\mu = (\partial \mu/\partial P)_{T,X}\, dP + (\partial \mu/\partial X)_{T,P}\, dX$$

which, by (30), becomes

$$d\mu = (V/3)\, dC + [2\, V_o\, (1 + \sigma)\, C/3\, E_y]\, dC \quad \ldots\ldots\ldots\ldots\ldots\ldots (31)$$

For stresses less than the breaking-strength of rocks under normal conditions C/E_y will be of the order of 10^{-3} or less, and σ is about 0.25 - 0.30. Thus the second term in (31) will usually be very small compared with the first, and may probably be neglected in most practical applications. We are left then with the remarkably simple result

$$d\mu = V\, dP = (V/3)\, dC \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (32)$$

The potential is thus increased by a compression, decreased by traction. The corresponding expression for the depression of the melting point would be

$$-\Delta T = TVC/3\, \Delta H \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (33)$$

where ΔH is the heat of melting. This quantity ΔT is considerably larger than that given by Riecke, the latter corresponding to the second term in the right-hand side of (31) which we have neglected.

Apart from numerical coefficients, the two terms on the right-hand side of (31) correspond respectively to the relations (9a) and (9b), derived by Goranson. According to the present theory, the change in potential on any surface is the sum of the changes which Goranson assigns respectively to stressed and free surfaces. Neglecting (9b), GORANSON [1940, p. 1029] has obtained an expression for the rate of creep which agrees well with experimental results. Eq. (31) would lead to a similar agreement and would, in addition, obviate the somewhat arbitrary neglect, in Goranson's theory, of his term (9b).

Pure shear--As a shear stress of magnitude S is equivalent to a traction across one plane and an equivalent compression across a perpendicular plane, the variation of the chemical potential by (32) is the sum of two equal terms of opposite sign and is thus zero, to the approximation involved in neglecting the second term in the right-hand side of (31). The effect of pure shear on the chemical equilibrium of an elastic solid appears therefore to be very small.

Aeolotropic elastic bodies--If we consider now the case of aeolotropic bodies under simple linear compression it will be apparent from (31) that the potential will depend on the orientation of the body with respect to the compression, as the values of σ and E_γ depend on direction within the crystal. Thus two crystals oriented differently will in general have different potentials, and the one with the lower potential would tend to grow at the expense of the other. One might expect that this effect would lead to the development of an oriented fabric, all crystals of the same mineral in a given rock tending to align themselves in a common orientation corresponding to the least possible value of the potential. Differences in elastic moduli in different directions are usually small. For instance, Young's modulus parallel to the optic axis of quartz at 0° C is 10.297×10^{11} dynes/cm^2, whereas the modulus in a direction normal to this axis is 7.86×10^{11} [BIRCH, 1942, p. 70]. Thus the differences in potential of two crystals oriented at right angles to each other would be very small, of the order perhaps of a few tenths of a calorie. The corresponding differences in solubility, vapor pressure, and other factors would in many cases be of the same order as other differences arising from other causes (such as grain size, impurities, and surface energies). Mechanical rotation of the crystals or internal gliding would probably be generally more effective in producing an oriented fabric.

Non-homogeneous stress--It has been shown above that in the case of homogeneous stress the potential of an elastic body is increased or decreased uniformly. There is no tendency for the solid to undergo solution at some points while deposition would occur simultaneously on other faces; it is the solid as a whole which tends to dissolve. This, of course, is no longer true if the stresses are not homogeneous, for the value of the mean pressure P would vary from point to point, and the change in chemical potential would accordingly be a function of position in the body. Thus there would in general be a tendency for the solid to go into solution at places where the stresses are more concentrated, as at points of mutual contact of hard grains, while reprecipitation might occur elsewhere. Experiments by RUSSELL [1935] illustrate this case.

Non-elastic bodies--If we turn now to a consideration of bodies in which the state of strain under given stress depends on time, it may become important to determine the distribution of the potential in the non-equilibrium state before the body has reached a stable configuration. Such a problem cannot be dealt with in classical thermodynamics, and additional assumptions become necessary.

In all cases, whether the body be elastic or not, the stress may be resolved into a mean pressure P and a shearing stress such as X. As fluids are usually assumed to be elastic with respect to changes in volume resulting from hydrostatic pressure, the method of the preceding paragraph remains valid as far as the mean pressure is concerned: We still have a variation $d\mu'$ of the potential resulting from the mean pressure which is given by $d\mu' = V\,dP$, where P is defined by (15).

To compute the term $d\mu''$ arising from the shearing stress X, one might proceed as follows: Assume that at any stage of the deformation the velocity $\underline{v}$ with which a particle moves from one configuration to another is proportional to the gradient of the potential at that point

$$\underline{v} = B \operatorname{grad} \mu'' \qquad (34)$$

where B is a constant depending on the nature of the substance; this is in fact the basic assumption of the theory of diffusion. On the other hand, it should be possible to determine the velocity at any point from the mechanical equations [illegible]on; for instance, in a Newtonian liquid with viscosity η

the components v_1, v_2, v_3 of the velocity vector are given by the classical relations [LAMB, 1932, p. 574]

$$\left.\begin{aligned} X_1 &= -P - (2/3)\,\mathrm{div}\,\underline{v} + 2\eta\,\partial v_1/\partial x_1 & X_4 &= \eta\,(\partial v_3/\partial x_2 + \partial v_2/\partial x_3) \\ X_2 &= -P - (2/3)\,\mathrm{div}\,\underline{v} + 2\eta\,\partial v_2/\partial x_2 & X_5 &= \eta\,(\partial v_1/\partial x_3 + \partial v_3/\partial x_1) \\ X_3 &= -P - (2/3)\,\mathrm{div}\,\underline{v} + 2\eta\,\partial v_3/\partial x_3 & X_6 &= \eta\,(\partial v_2/\partial x_1 + \partial v_1/\partial x_2) \end{aligned}\right\} \quad \ldots\ldots (35)$$

where $X_1 \ldots X_6$ are the components of stress, and P has the same significance as in (15). Having obtained the values of $\underline{v}$ at all points by solving these equations, the chemical potential could be found easily by simple integration.

If we could imagine, for instance, a viscous fluid in the form of a prism subjected on both ends to a compression C parallel to the axis x_3 and flowing out on the sides, we would find, assuming a steady state in which $\mathrm{div}\,\underline{v} = 0$, that the components of the velocity at any point with coordinates x_1, x_2, x_3 are

$$v_1 = C\,x_1/6\eta \qquad v_2 = C\,x_2/6\eta \qquad v_3 = -C\,x_3/3\eta \quad \ldots\ldots (36)$$

the velocity at the center (0, 0, 0) being 0 by reason of symmetry. Integration of (34) then leads to the result

$$\mu'' = (-C/12\,B\eta)\,(2\,x_3^2 - x_1^2 - x_2^2) \quad \ldots\ldots (37)$$

This term varies continuously from point to point, being maximum at the center of the stressed faces ($x_1 = x_2 = 0$). The difficulty, however, is that of calculating the numerical value of B. If it is assumed that the displacement of a particle from one position to the next is essentially a process of self-diffusion, it is easily seen that $B = D/RT$, where D is the diffusion coefficient. Using Eyring's results for the value of the diffusion coefficient and Newtonian viscosity according to the theory of absolute reaction rates [GLASSTONE and others, 1941], we get

$$\eta B = (\lambda^2/V)\,\exp\,[(\Delta G_{dif} - \Delta G_{vis})/RT] \quad \ldots\ldots (38)$$

where λ is the distance between two successive positions of the particle in the direction of flow, and ΔG_{dif} and ΔG_{vis} are respectively the free energies of activation for the processes of diffusion and viscous flow. Eyring has shown also that for metals the process of diffusion does not involve the migration of individual atoms into vacant lattice positions, but rather the rotation past each other of pairs of atoms, the additional free volume or "hole" required to allow this rotation being only a small fraction (about 1/8) of the mean atomic volume. Viscous flow, on the contrary, presumably involves larger units and requires larger holes, so that ΔG_{vis} should exceed ΔG_{dif} by an amount corresponding to the energy required to make a hole sufficiently large, which would be a large fraction of the free energy of vaporization. Thus one would expect that for silicates minerals ($\Delta G_{dif} - \Delta G_{vis}$) would be negative and of the order of several thousand calories, say 20,000 cal. As λ is of the order of 10^{-8} cm, $B\eta$ at ordinary temperature would be of the order of 10^{-1} and μ'' would be comparatively small. Solids undergoing non-elastic deformation cannot be assimilated to Newtonian liquids, their "viscosity" being a function of the stresses and other factors (such as time and previous history of the specimen). Hence the equations in (35) are not valid, and the integration of (34) is not as simple as illustrated here. There does not seem to be any means at present of computing $d\mu''$ in such cases; all that may be said is that, presumably, the closer the body approaches elastic behavior, the smaller the term.

Summary and conclusions--The conclusion is reached here that the effect of non-hydrostatic stress on the chemical potential (and hence on the solubility, vapor pressure, melting point, and other factors) of a solid consists of two terms. The first, which applies to elastic and non-elastic substances, is given by the simple relation

$$d\mu = V\,dP$$

where V is molar volume and P is the mean pressure defined in terms of the principal stresses X_1, X_2, X_3 by the relation

$$-P = (X_1 + X_2 + X_3)/3 \quad \ldots\ldots (15)$$

For elastic bodies, the second term in (31) is probably negligible in most practical cases, so that the effect of pure shear (P = 0) on such bodies should be very small. Both the first and second terms are the same at all points in a homogeneously stressed elastic solid.

For non-elastic substances, the second term $d\mu''$ is a continuous function of position in the body. The value of this term cannot be computed unless additional assumptions are made concerning the mechanism of deformation; but it appears to be small in very viscous or nearly elastic substances. Again, the effect of shear on the chemical equilibrium of such bodies would be small; but it is conceivable that this effect might become large in bodies which depart sufficiently from elastic behavior.

As regards the possible existence of antistress minerals, that is, minerals whose field of stability is decreased by non-hydrostatic stress, it may be noted that, to a first approximation, the effect of such stress is qualitatively the same as that of hydrostatic stress; antistress minerals should therefore also become unstable under high confining pressures, a conclusion which agrees with the observation that common antistress minerals (for example, leucite, nepheline, cordierite) have fairly large molar volumes [TURNER, 1948]. There is nothing in the present theory that leads to the prediction of the existence of stress minerals, that is, of minerals that could form only in presence of shear. This does not imply that non-hydrostatic stress, or more exactly the deformation resulting from such stress, cannot promote the formation of certain mineral assemblages; but this effect is believed to be due mostly to a catalytic action connected with the deformation. In other words, it is probably the effect of shear on the kinetics of certain reactions that makes it an important metamorphic agent.

Acknowledgments--The writer desires to express his thanks to L. H. Adams, R. W. Goranson, and Carl Eckart who have kindly read this manuscript at various stages in its preparation. P. Van Rysselberghe has suggested many improvements which are gratefully acknowledged here.

References

BIRCH, F. (Ed.), Handbook of physical constants, Geol. Soc. Amer. Spec. paper 36, 1942.
BRIDGMAN, P. W., On the effect of general mechanical stress on the temperature of transition of two phases, Phys. Rev., v. 7, pp. 215-223, 1916.
GIBBS, J. W., Scientific papers, Longmans, Green Co., 434 pp., 1906.
GLASSTONE, S., K. J. LAIDLER, and H. EYRING, The theory of rate processes, McGraw-Hill Co., New York, 611 pp., 1941.
GORANSON, R. W., Thermodynamic relations in multi-component systems, Carnegie Inst. Wash. Pub. 408, 329 pp., 1930.
GORANSON, R. W., Flow in stressed solids, an interpretation, Bull. Geol. Soc. Amer., v. 51, pp. 1023-1034, 1940.
LAMB, H., Hydrodynamics, Cambridge Univ. Press, 738 pp., 1932.
RICE, J., in A commentary on the scientific writings of J. W. Gibbs (edited by Donnan and Haas), Yale Univ. Press, v. 1, 742 pp., 1936.
RIECKE, E., Ueber das Gleichgewicht zwischen einem festen, homogen, deformirten Koerper und einer fluessigen Phase, Ann. Physik., v. 54, pp. 731-738, 1895.
RUSSELL, G. A., Crystal growth in solution under local stress, Amer. Mineral., v. 20, pp. 733-737, 1935.
SOKOLNIKOFF, I. S., Mathematical theory of elasticity, McGraw-Hill Co., New York, 373 pp., 1946.
TURNER, F. J., Evolution of the metamorphic rocks, Geol. Soc. Amer., Mem. 30, 1948.
TYRRELL, G. W., The principles of petrology, Methuen, London, 349 pp., 1926.
WILLIAMSON, E. D., The effect of strain on heterogeneous equilibrium, Phys. Rev., v. 10, pp. 275-283, 1917.

Department of Geological Sciences,
University of California,
Berkeley 4, California

(Communicated manuscript received November 6, 1950;
open for formal discussion until September 1, 1951.)

Transactions, American Geophysical Union Volume 32, Number 2 April 1951

THE CARUPANO AREA AND ITS RELATION TO THE TECTONICS OF NORTHEASTERN VENEZUELA

J. C. Maxwell and Gabriel Dengo

(Princeton contributions to Caribbean Geology, no. 3)

Abstract--The Venezuelan Coast Range in the vicinity of Carupano is lithologically and tectonically similar to the mountainous belt of low grade metamorphic rocks lying south of Caracas. Phyllites and slightly metamorphosed limestones in both areas show evidence of southward thrusting and overfolding. Along the coast north of Caracas and on the island of Margarita the metamorphic rocks have been overturned to the north. The coast ranges are believed to be part of a two-sided orogen with a northeasterly trending axis which passes south of Caracas and between Margarita and the mainland.

Both metamorphics and Cretaceous sedimentary rocks are extensively faulted. West of El Pilar a system of northwesterly striking faults or fissures localizes hot springs and sulphur deposits; one such fault separates the Cretaceous sedimentary rocks from metamorphic rocks.

Available evidence indicates that the Cretaceous sediments are not composed of detritus eroded from the low grade metamorphics of the Coast Range. Furthermore, these sediments are nowhere known to be in sedimentary contact with the Coast Range rocks. In the Carupano area, at least, it seems probable that the phyllites and limestones of the Coast Range have been thrust and overfolded southward toward and perhaps onto the Cretaceous sediments, though the present contact appears to be a large fault or series of faults upthrown relatively on the south side.

Introduction

A research program has been carried on for a number of years by the Department of Geology of Princeton University in the Caribbean region. The chief aim of the program is to attempt to relate geology to available geophysical information and thereby attain a better understanding of mountain-building processes. Since 1946 research in Venezuelan geology has been carried on jointly with the Instituto Nacional de Geología y Minería, A. Schwarck, Director. Correlation of geophysical work at sea with the geology of the islands and mainland of South America has been supported for the past two years by a contract between Princeton University and the Office of Naval Research. Detailed mapping has been carried out in Tobago [MAXWELL, 1948] and in three areas between the coast north of Caracas and the town of San Juan de los Morros (see Fig. 1). The study of the Caracas area has been completed [DENGO, in press], and the two areas to the south are being investigated by R. J. Smith and J. C. MacLachlan. Reconnaissance investigations have been carried out in the Coast Range to the east and west, approximately within the area outlined by the towns named in Figure 1. Other reconnaissance surveys have been made on Curacao and Orchila, and somewhat more detailed work has been done on Bonaire, Margarita [HESS and MAXWELL,

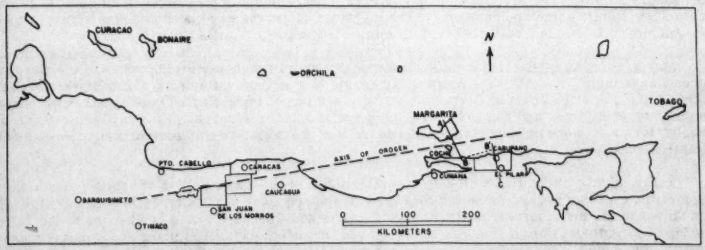


Fig. 1--Index map, northeastern Venezuela and adjacent islands

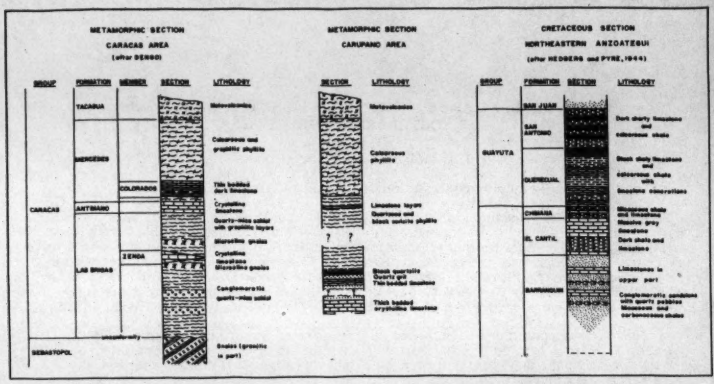


Fig. 2--Stratigraphic sections; metamorphic rocks of the Serranía de la Costa (Caracas and Carupano areas) and unmetamorphosed Cretaceous sediments of the Serranía del Interior (northeastern Anzoategui)

1949] and in the vicinity of Carupano. The area of detailed work between Caracas and San Juan de los Morros was selected because it supplies a cross section of the strongly deformed and metamorphosed portion of the orogen; the Margarita and Carupano areas together give a similar but less continuous cross section.

HESS [1938] made a preliminary interpretation of the gross relations of geology and geophysical data in the West Indies. Considerable gravity work has since been done in the area, principally by Ewing and Woollard and their associates, and final results are not yet available. No attempt is made herein, therefore, to correlate our more recent geological work with the geophysical data.

Stratigraphy

Lithology--The metamorphosed rocks of the Carupano area consist of more or less recrystallized limestones, quartzose, sericitic, and calcareous phyllites, orthoquartzites, coarse quartzose grits, and metavolcanic green schists, as illustrated in Figure 2. In the southeastern part of the area the limestones have been very little recrystallized and the fine grained clastic sediments have been converted to quartz-sericite phyllite and black, lustrous sericite phyllite. The degree of metamorphism increases somewhat to the northward, however. North of a line which extends from Chamariapa on the west, through a point about a mile south of Carupano and south of Rio Caribe on the east, the limestones have been completely recrystallized to marbles which carry accessory zoisite. The sericite-quartz phyllites likewise contain zoisite and a small amount of colorless, faintly anisotrophic garnet. The metavolcanic rocks have been competely recrystallized to epidote-actinolite and actinolite-albite-zoisite schists with a little chlorite.

Age and correlation--No direct evidence of the age of the metamorphic rocks of the Carupano area is available. Fossils were found in limestone in a stream valley east of the limestone quarry, three kilometers southeast of Carupano, but they are large, thick shelled pelecypods, with completely recrystallized and somewhat crumpled shells and are apparently unidentifiable. Some thick walled forms of more or less circular cross section are suggestive of rudistids but cannot be definitely identified.

Lithologically these rocks closely resemble those of the upper part of the metamorphic section of the Caracas region; as shown by Figure 2, the sequence of rock types is quite similar. The thickness of the metamorphic section in the Caracas and Carupano areas is likewise of the same order of magnitude, though complex structure and imperfect exposures make accurate measurements impossible. The Caracas group is between 1500 and 3000 m thick and the exposed metamorphics in the Carupano area have a maximum thickness of 3100 m. The writers believe that

lithologic, structural, and metamorphic similarity along the strike is reasonable evidence that the metamorphic sequences in the Caracas and Carupano areas are of approximately the same age.

Evidence has been presented that the Caracas group is at least partly Cretaceous in age [summarized by HESS and MAXWELL, 1949, p. 1863], hence the Carupano metamorphics are probably also partly Cretaceous. Very similar phyllites and limestones are exposed in the North Range of Trinidad, where late Jurassic ammonites have been found in limestone interbedded with phyllites [HUTCHISON, 1938, 1939], and where highly contorted but little metamorphosed calcareous shales near the east end of the range contain Cretaceous fossils [THOMAS, 1935; TRECHMANN, 1935]. These shales are interbedded with andesetic tuffs and breccias (specimens furnished by K. W. Barr), suggesting a possible correlation with the metavolcanics of the Carupano section. Evidence thus seems to indicate a late Mesozoic (late Jurassic-Cretaceous) age for the metamorphic rocks of the Carupano area.

The correlation of the Carupano metamorphics with those on nearby Margarita is even less certain than between the Carupano and Caracas areas. This is perhaps to be expected since the Margarita area is across the strike and, if our interpretation is correct, on the opposite side of the orogen. Nevertheless the rocks represent a similar sedimentary facies although a part of the Margarita rocks have been much more intensely metamorphosed. In general both areas are characterized by thick quartzose metasediments which are sericitic quartzites and phyllites near Carupano and are garnetiferous quartz-muscovite schists and gneisses on Margarita. Marbles are interbedded with the quartzose metasediments in both areas and in both the youngest beds are metavolcanics, though in Margarita these are hornblende-albite-zoisite gneisses and amphibolites. The only conspicuous difference between the two areas is the absence on Margarita of the thick calcareous phyllite sequence which is present in both the Carupano and Caracas areas.

Relation between metamorphic rocks and unmetamorphosed sediments

Miocene (?) clastic sediments--In the vicinity of El Pilar, poorly consolidated sandstones and silty shales rest unconformably on the phyllites and dip gently to steeply to the south (see Fig. 3). These sediments consist mainly of sharply angular quartz grains, very little sorted, in a silty matrix, with little or no feldspar. They contain abundant fragments of silvery gray phyllite and fine quartzite and an occasional piece of detrital limestone. Fine white mica is present in the matrix. Only a very few heavy minerals are present and of these leucoxene is by far the most abundant; green tourmaline and zircon are common and rutile and hypersthene were tentatively identified.

These sediments are of the sub-graywacke (or low rank graywacke) facies. They probably were formed by the rapid stripping of weathered debris from the surface of the metamorphic rocks and the dumping of this debris in shallow water without appreciable subsequent reworking or sorting. The interbedded silty shales contain abundant plant fragments. The age of these beds has not been established, but Bucher (unpublished map) regards them as Tertiary, probably Miocene or Pliocene.

Cretaceous sediments--South of the metamorphics and west of El Pilar steeply dipping rocks of Barranquín and possible El Cantil lithology are poorly exposed. Black, coarse, carbonaceous grits, and gray, thick bedded, crystalline limestone form most of the outcrops. Black, pyritic, silty shales are exposed at the sulphur mine. Some of the limestones are richly fossiliferous, but the grits and unfossiliferous limestone can scarcely be distinguished from similar rocks in the metamorphic sequence to the north and east.

Most of the Cretaceous sandstones of this area are orthoquartzites but locally the coarse sandstones of the Barranquín contain considerable decomposed chalky feldspar. Heavy minerals of both the Barranquín and the overlying "Bergantín beds" (Chimana-El Cantil) are a simple zircon-leucoxene suite with minor amounts of ilmenite, tourmaline and rutile [HEDBERG, 1937]. Coarse white mica is abundant in Barranquín and El Cantil (?) sandstone samples collected by the writers east of Cumana and near El Pilar. The Barranquín sediments appear to represent an alternation between coastal swamp and shallow water marine environment with conditions later becoming more persistently marine [HEDBERG and PYRE, 1944]. The mineral assemblage suggests derivation from thoroughly weathered and decomposed granitic rocks or metamorphic rocks of a much higher grade of metamorphism than the phyllites exposed to the north. So far as we can determine no fragments of phyllite occur in these Cretaceous sediments. Moreover, none was noted in the area west of El Pilar where the phyllites and sediments outcrop within a short distance of each other.

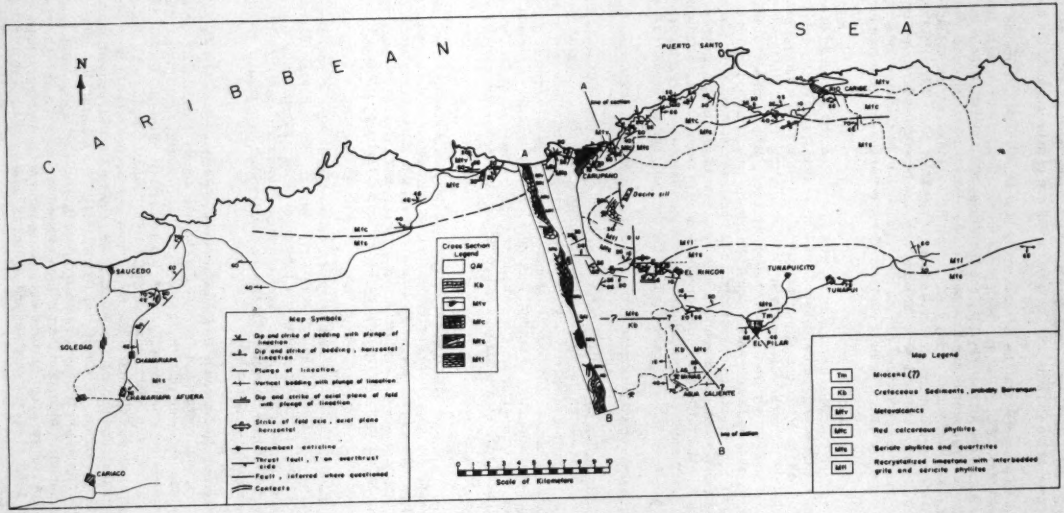


Fig. 3--Geologic map and cross section, Carupano area

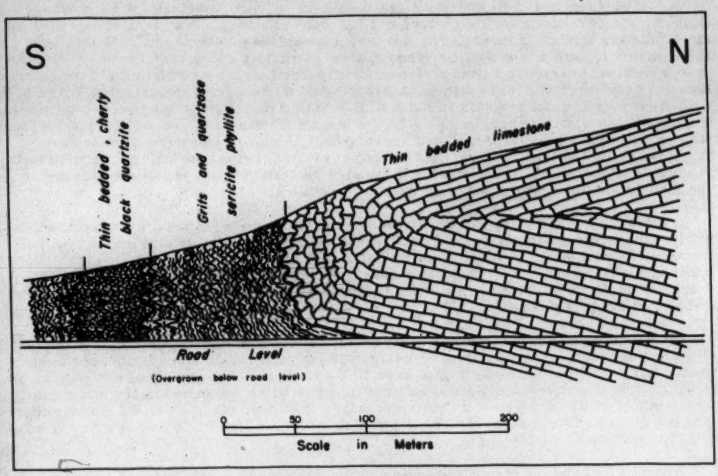


Fig. 4--Sketch of recumbent anticline exposed on Carupano-El Rincón road, five km west of El Rincón

Three possible relationships exist between the metamorphics and the Cretaceous sediments exposed to the southward: (1) the metamorphics are older and are overlain unconformably by the Cretaceous sediments; (2) the metamorphics and Cretaceous sediments are essentially of the same age and the metamorphics have been overthrust and overfolded onto the sediments; or (3) the metamorphics represent younger sediments than those exposed immediately to the south. Unfortunately the contact follows the Cariaco trough and a line of similar depressions to the east and is nearly everywhere buried under alluvium. Whatever the relative ages of the metamorphics and Cretaceous sediments may be, their contact is probably a major fault zone [HEDBERG and PYRE, 1944], so that convincing evidence of the age relationship is difficult to obtain. We do not believe that (1) can be true, however, because of the presence of late Jurassic and Cretaceous rocks among the metamorphics. Furthermore all evidence indicates the unmetamorphosed Cretaceous sediments could not have been derived by erosion of the metamorphic rocks exposed to the northward; in fact the sediments and metasediments represent the same sedimentary facies, had similar source areas, and were deposited in similar environments.

At present we are unable to choose definitely between (2) and (3). Lithologically the Carupano metamorphics correlate best with the upper part of the metamorphic section of the Caracas area and with uppermost Barranquín and later sediments of the Cretaceous section of northeastern Anzoategui (see Fig. 2). At first by lithologic similarity [AGUERREVERE and ZULOAGA, 1937, 1938] and later on the basis of microfossils [DUSENBURY and WOLCOTT, 1949] a late Cretaceous age has been demonstrated for the upper part of the Caracas metamorphic section. The metamorphics of the Carupano-El Pilar region therefore may be, on the whole, somewhat younger than the Barranquín sediments exposed just to the south. Such a relationship could result if the fairly recent faulting responsible for the Cariaco trough had a large vertical component, upthrown relatively on the south side.

Structure

Southward overturning and overthrusting characterizes the rocks of the Carupano area (see Fig. 3). The predominant dip of the metamorphic rocks is about 35° to 45° north or northwest, although measured dips vary from horizontal to vertical and in a few places southerly dips were observed.

Along the road west of El Rincón a large recumbent anticline, overfolded to the south, is well exposed. Figure 4 illustrates the character of the nose of the anticline as exposed in a road cut five kilometers west of El Rincón. The dark gray thin-bedded limestone and black thin-bedded cherty quartzite, although essentially vertical, have been crumpled into small folds with horizontal axial planes. The degree and attitude of crumpling is identical in the quartzite and limestone. Both were equally plastic to the deforming stress. East of the outcrop illustrated in Figure 4, the road drops steeply to the lowlands on which El Rincón is built and along this road overturned beds of quartzite and quartzose phyllite dip northward beneath the older limestones. West of the exposure shown in Figure 4 a large northerly trending fault, occupying a prominent valley, brings quartzose phyllite against the limestone. A zone of southward dips and vertical, crumpled beds exposed along the road two kilometers to the west of the fault probably represents the nose of the recumbent anticline as expressed in the quartzose phyllites.

Throughout the Carupano area the limestones and quartzose phyllities are characterized by small folds overturned to the south. The dip of the axial planes of these folds varies from horizontal to 55° northward. In many places the rocks have been broken and thrust southward along minor thrust faults some of which developed along the axial planes of small overturned folds. Only a few of the minor folds and thrust faults are shown in Figure 3; most of them could not be included on a map of this scale.

Structures within the calcareous phyllite tend to be less uniformly oriented than in the rest of the metamorphics. East of Carupano, for example, the upper and lower contacts of this unit trend generally a little north of east, but in detail the rocks have been crumpled into northward plunging cross folds. Small scale overthrusting also took place, but in an easterly and westerly direction rather than to the south as is characteristic of the rest of the area. To a lesser degree the calcareous phyllite and overlying metavolcanics, wherever exposed, show easterly and westerly dips and other evidence of cross folding.

Wherever bedding can be recognized, the metamorphic rocks of this area have bedding plane schistosity. Even in the homogeneous sericite phyllites where bedding cannot be distinguished, the schistosity is essentially parallel to bedding in nearby metasediments. A similar parallelism of schistosity and bedding has been observed in the Caracas area, in Margarita and in Tobago, exceptions occurring very rarely on the crests of small local folds. Schistosity follows bedding around the nose of the recumbent fold illustrated in Figure 4 so that it cannot be assumed that the schistosity developed as axial plane schistosity on the flanks of isoclinal folds. Perhaps the schistosity developed by mimetic recrystallization, but there is no obvious reason why such a mechanism should affect rocks of different grades of metamorphism on both sides of this particular orogen.

The lineation recorded on Figure 3 consists mostly of crumples and minute wrinkles on bedding surfaces. Locally pencil lineation has resulted from extreme development of the crumples, particularly in the calcareous phyllites. A less pronounced pencil lineation characterizes the more massive metavolcanics also, but in these rocks is caused by a sub-parallel orientation of fine actinolite needles and rod-like aggregates of apidote and clinozoisite grains. Wherever their relationship could be observed pencil lineation and lineation due to wrinkling and crumpling were parallel and were also parallel to axes of minor folds. In general the lineations plunge gently to steeply to the west or northwest though in the vicinity of the large recumbent anticline (see Fig. 4) most of the lineations and minor fold axes are nearly horizontal.

Both the metamorphics and the Cretaceous sediments have been cut by faults, most of which have a northwesterly trend and appear to be normal faults. The large fault which cuts the recumbent anticline west of El Rincón is of this type though its strike is approximately north-south. At Agua Caliente a series of fumaroles and hot springs smelling strongly of H_2S issue from steeply dipping grits and fossiliferous limestones of Barranquín lithology. The hot springs are aligned along a stream valley trending N35° W. At the abandoned sulphur mine a kilometer northwest of Agua Caliente sulphur was mined from two fumarole zones in steeply tilted carbonaceous grits, sandstones and black pyritic silty shales. Siliceous sinter is abundant and the grits and shales are locally bleached white. At the most northwesterly locality the bleached fumarole zone is about 400 yd long, 50 to 100 yd wide and trends N20° W. The trend of the other fumarole zone was not determined.

The geologic relationships suggest that a northwesterly trending fault separates the Cretaceous sediments and metamorphic rocks east of Agua Caliente though the fault itself was not seen. It is perhaps significant that the northwesterly trending faults and fissures of the Agua Caliente area,

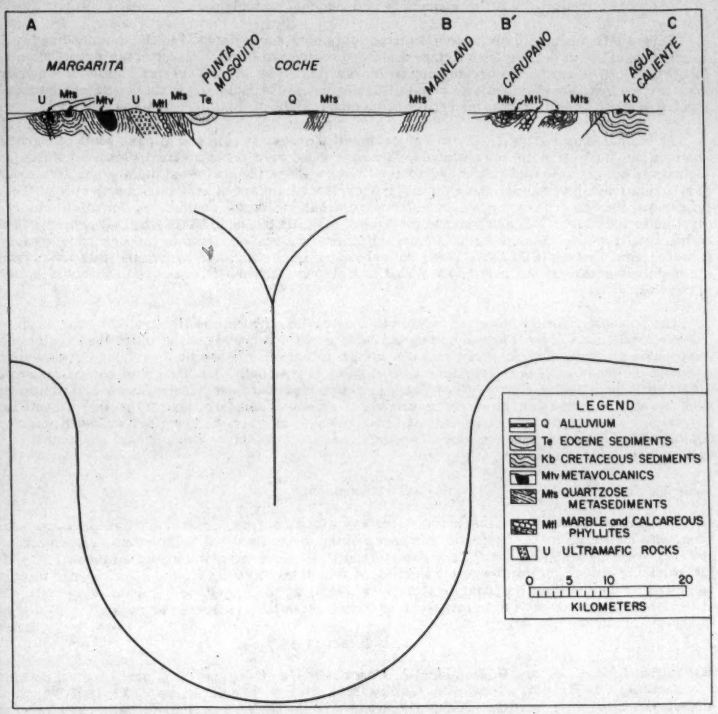


Fig. 5--Geologic cross section, Margarita-Carupano area illustrating possible relation to crustal downbuckle; for location of cross section see Fig. 1

if projected northward, intersect the Carupano-El Rincón road about three kilometers west of El Rincón, and at this place a strong odor of hydrogen sulphide was noted at several points along the road. In this general area also, four and one-half miles south of Carupano, the productive area of a long-abandoned silver, lead, and copper district trends NW-SE though the individual veins are said to trend NE-SW [S., 1874].

Igneous activity

Aside from the metavolcanics which are the youngest of the metamorphic rocks only one outcrop of igneous rock was observed in the Carupano area. Near the limestone quarry three kilometers south of Carupano a quarry has been opened in a mass of very fresh pale grayish green dacite porphyry, with euhedral crystals of quartz and crystals and crystal aggregates of sodic oligoclase. The dacite is overlain by grits and quartzose phyllites which dip 35° to the west northwest and the contact is conformable to the dip. Although its bottom contact was not observed, the mass is over 150 ft thick and is believed to be a sill. Its completely fresh, unsheared and massive character indicates the dacite was intruded after the metamorphism. Hot springs, fumaroles, sulphur deposits and possibly the metalliferous veins west of El Rincón may be evidence of similar relatively recent igneous activity.

Carupano area and regional tectonics

Figure 5 is a geologic cross section from Margarita southeastward to the mainland and, with an offset parallel to the regional strike, continued southward through Carupano to Agua Caliente (see Fig. 1). The northward overturning on Margarita and southward overturning in the Carupano area are evident. On the southeast coast of Coche and on the mainland to the south, northwestward dipping sericite and muscovite quartzites were observed by Hummelinck [RUTTEN, 1940].

As indicated on Figure 1, the axis of a two-sided orogen is believed to pass south of Caracas and between Margarita and the mainland. Because of the high grade metamorphism on Margarita the axis is put close to that island and north of Coche where the northwest dipping quartzites suggest a relationship to the mainland. The Caracas-Margarita areas are on the north side of the orogen and the San Juan de los Morros-Carupano areas are on the south side. Parallel belts of ultramafic rocks lie north and south of the orogen axis [HESS and MAXWELL, 1949, Fig. 2]. Large bodies of ultramafic rocks outcrop in Margarita, but none was observed in the Carupano area. However, Hummelinck [RUTTEN, 1940] collected a suite of antigorite serpentine-talc rocks from the mainland southeast of Coche, 60 km west of Carupano, and these rocks are probably altered peridotite.

The possible relationship of the orogen to a crustal downbuckle is illustrated by Figure 5. The metasediemnts of the Carupano area were deposited in a seaway along which the crustal downbuckle later developed. Sediments now known as Barranquín and the overlying Cretaceous rocks on the other hand were laid down considerably to the south. Intense compression resulting from crustal shortening above the downbuckle produced outward overturning and overthrusting of rocks away from the axis. It seems reasonable to assume, therefore, that the metasediments and Cretaceous sediments could be essentially the same age, as suggested by other evidence, but deposited at some distance from one another and brought into contact by the crustal shortening resulting from the downbuckling of the crust.

Acknowledgments

K. W. Barr of Trinidad Leaseholds, Ltd., was with us during our field work in the Carupano area. His knowledge of the metamorphic rocks of the North Range of Trinidad was extremely helpful. We also wish to thank H. D. Hedberg, and H. H. Hess for criticizing the manuscript and for providing much useful information bearing on this study. During the field work Dengo was employed by the Instituto Nacional de Minería y Geología, Ministerio de Fomento, Venezuela. We are indebted to this organization for permission to publish the results of the work.

References

AGUERREVERE, S. E., and G. ZUOLOAGA, Observaciones geológicas en la parte central de la Cordillera de la Costa, Venezuela, Geol. y Min., Bol. T. 1, no. 2-4, pp. 3-22, 1937.

AGUERREVERE, S. E., and G. ZUOLOAGA, Nomenclatura de las formaciones de la parte central de la Cordillera de la Costa, Geol. y Min., Bol. T. 2, no. 2-4, pp. 281-284, 1938.

DENGO, GABRIEL, Geología de la region de Caracas, Revista de Fomento, Caracas, Venezuela, in press.

DUSENBURY, A. N., and P. P. WOLCOTT, Rocas metamórficas cretácicas en la Cordillera de la Costa de Venezuela, Assoc. Ven. de Geol., Min. y Pet., T. 1, no. 1, pp. 17-26, 1949.

HEDBERG, H. D., Stratigraphy of the Rio Querecual section of Northeastern Venezuela, Geol. Soc. Amer. Bull., v. 48, pp. 1971-2024, 1937.

HEDBERG, H. D., and A. PYRE, Stratigraphy of Northeastern Anzoategui, Venezuela, Amer. Assoc. Petrol. Geol., Bull., v. 28, pp. 1-28, 1944.

HESS, H. H., Gravity anomalies and island arc structure with particular reference to the West Indies, Proc. Amer. Phil. Soc., v. 79, pp. 71-96, 1938.

HESS, H. H., and J. C. MAXWELL, Geological reconnaissance of the island of Margarita, Geol. Soc. Amer. Bull., v. 60, pp. 1857-1868, 1949.

HUTCHISON, A. G., Jurassic ammonites in the Northern Range of Trinidad, Geol. y Min., Bol., T. 2, no. 2-4, p. 262, 1938.

HUTCHISON, A. G., Geological note, Amer. Assoc. Petrol. Geol., v. 23, p. 1243, 1939.

MAXWELL, J. C., Geology of Tobago, British West Indies, Geol. Soc. Amer. Bull., v. 59, pp. 801-854, 1948.

RUTTEN, L., On the geology of Margarita, Cubagua and Coche (Venezuela), Proc. Nederl. Akad. van Weten., v. 43, pp. 828-841, 1940.

S., J. H. D., The silver, lead, and copper mines of Carupano, Eng. Min. J., v. 18, pp. 226-227, 1874.

THOMAS, H. D., On some sponges and a coral of Upper Cretaceous age from Toco Bay, Trinidad, Geol. Mag., v. 72, pp. 175-179, 1935.
TRECHMANN, C. T., Fossils from the Northern Range of Trinidad, Geol. Mag., v. 72, pp. 166-175, 1935.

Department of Geology,
Princeton University,
Princeton, New Jersey

(Manuscript received July 21, 1950; presented at the Thirty-First Annual Meeting, Washington, D. C., May 2, 1950; open for formal discussion until September 1, 1951.)

RESEARCH AT THE COLORADO SCHOOL OF MINES IN SUBJECTS RELATED TO THE MECHANICS OF ROCK FAILURE

Clifton W. Livingston

Abstract--The paper presents the results of experiments at Colorado School of Mines in subjects related to the mechanics of rock failure. A brief review of Fenner's hypothesis of the distribution of stress around circular and elliptical openings is presented and field evidence cited which supports the hypothesis.

An impact loading device useful in studies of rock failure is described, and the attitudes of strain lines in a brittle, lacquer-coated tunnel model as obtained with the impact loading device are compared with the directions and magnitudes of the principal stresses obtained using an interferometer. The distribution of the strain lines is compared with the stress distribution around the opening, and a strain pattern produced by impact loading is compared with one produced by static loading. Results indicate that the apparatus and techniques can be used to determine the direction of principal stress and to compare static and impact loads producing similar strain patterns.

Introduction

Many problems of mining engineering are a direct result of a lack of knowledge of the fundamentals of rock failure. Probably ignorance of such fundamentals is responsible also for many of the unsolved problems of geology and geophysics. Progress of research in this field has been rapid during the past ten years. Recently I have become interested in research in mining engineering related to rock failure, and have suggested several coordinated research projects to graduate students in mining engineering at the Colorado School of Mines. The work that they have completed is the subject of this paper. In a sense, the work presented is of a preliminary nature for it marks the beginning of additional experiments dealing with the application of fundamentals of rock failure in mining engineering.

A review of theoretical studies dealing with the elastic behavior of rocks

RICHARD P. SCHOEMAKER [1948], a student at Colorado School of Mines from Delft, The Netherlands, chose "A review of rock-pressure problems" as the subject for a paper to be submitted in an undergraduate student prize contest sponsored by the American Institute of Mining and Metallurgical Engineers. His paper, a review of foreign literature dealing with the distribution of stress around underground openings and with subsidence phenomena observed in longwall mining, was judged to be the winning paper of the Sixth National Student Prize Paper Contest. Figure 1 is from Schoemaker's paper, and is adapted from the work of FENNER [1938]. The tangential stress distribution around circular openings and elliptical openings of various axis ratios has been calculated mathematically, assuming that the vertical load is uniformly applied and that the horizontal expansion induced by the vertical load is prevented by the surrounding rock. The results are based upon an assumed value of Poisson's ratio of 0.2.

General formulas have been derived by Fenner for the stress at the vertical and at the horizontal axes of an ellipse oriented with the "a" axis parallel to the vertical stress. The tangential stress at the vertical axis equals

$$S_V = [m/(1 - m)]\, P_1\, (2\, a/b + 1) - P_1 \text{ (Tension)} \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where a = the length of the vertical axis of the ellipse, b = the length of the horizontal axis of the ellipse, m = Poisson's ratio, P_1 = the vertical stress, and S_V = the tangential stress at the vertical axis.

The tangential stress at the horizontal axis equals

$$S_H = P_1\, (2\, b/a + 1) - [m/(1 - m)]\, P_1 \text{ (Compression)} \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where S_H = the tangential stress at the horizontal axis, and $[m/(1 - m)]\, P_1$ = the horizontal stress induced by the vertical load.

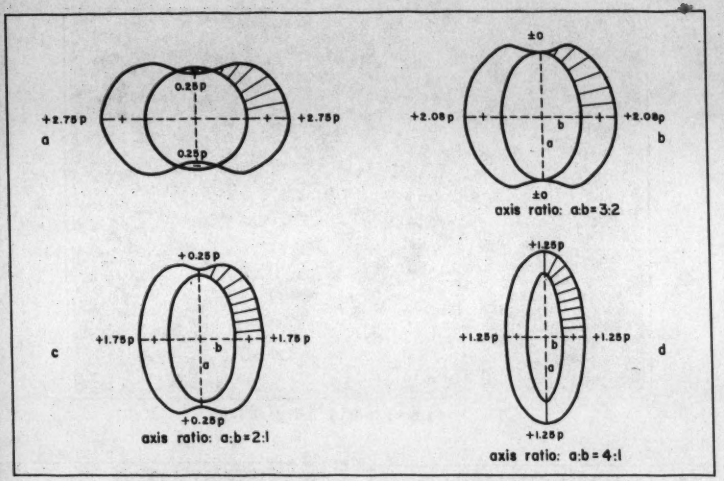


Fig. 1--Stress distribution around circular and elliptical openings; vertical loading and lateral confinement (after Fenner)

By letting S_V in (1) equal zero and solving for the axis ratio, Fenner has derived the following general equation.

$$a/b = [(1 - m)m - 1]/2 \quad (S_V = 0) \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Figure 1b, which Fenner terms "the pressure dome", has an axis ratio a/b equal to 3/2. At this axis ratio, the tangential stress at the vertical axis equals zero when m equals 0.2. This value of m is typical for many kinds of rock.

By equating (1) and (2) and solving for the axis ratio, Fenner has derived the following general equation for the condition in which the tangential stress is uniform at all points of the boundary.

$$a/b = 1/m - 1 \quad (S_V = S_H) \ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Figure 1d has an axis ratio a/b = 4. At this axis ratio the tangential stress at the vertical axis and at the horizontal axis are equal for a value of m = 0.2.

Results of field and laboratory research dealing with the elastic behavior of rocks

Field studies of natural arches and of the failure of cliffs--Figure 2 is a photograph of the Rainbow Natural Bridge in Arches National Monument near Moab, Utah. Figure 3 shows the shape of the arch as determined from a series of photographs and from the measurements shown. Both figures have been reproduced from the thesis of COGAN [1950, Fig. 11 and 12].

The axis ratio of the natural bridge corrected for the height of the canyon within the arch and multiplied by two to compare with the pressure dome of Fenner is

$$2 \times 208/274 = 1.52$$

The axis ratio a/b = 3/2 of the "pressure dome" ellipse of Figure 1b is for all practical purposes identical with the axis ratio 1.52 of the Rainbow Natural Bridge. Thus, it appears that the Rainbow Natural Bridge is a striking verification of Fenner's Hypothesis.

Fig. 2--Rainbow Natural Bridge in Utah

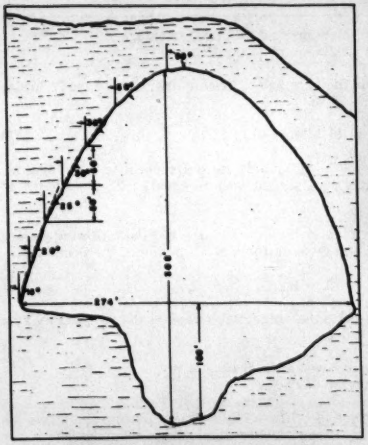


Fig. 3--General shape of Rainbow Natural Bridge (from a series of photographs)

Fig. 4--A cave at Moab, Utah, showing the mechanics of arching and slabbing

It is evident from an inspection of the photograph of the Rainbow Natural Arch that lateral deformation of the sides of the arch has been prevented by the mass of rock on both sides of the arch. Thus, the condition of loading is identical with the assumptions of Fenner. The sandstone of the arch is remarkably uniform in texture and is free from geologic planes of weakness. Thus, the condition of an ideal homogeneous medium assumed by Fenner is also satisfied. The position of the bridge relative to the present land surface and the lack of shear fractures in the sandstone surrounding the bridge are evidence that failure has occurred predominantly within the region where the strength of the rock in shear has not been exceeded. The nearly identical shapes of the arch of Rainbow Natural Bridge and the "pressure dome" ellipse indicate that Poisson's ratio for the sandstone of the arch is very nearly 0.2, and that the failure of the arch ceases as the value of the tensile stress approaches zero.

Figure 4 is a photograph of another natural arch located nearby in the same sandstone

Fig. 5--Close-up of rock slapping because of vertical pressure

formation. In this instance the arch is in its early stages of development. Plastic flow may have occurred at the buttress of the arch. The arch is flat in its early stages, but presumably steepens progressively as successive slabs fail. Whether each slab fails in pure tension or in combined shear and tension is unknown. Perhaps a study of the stress distribution around the opening at successive stages of development of the arch may provide evidence bearing upon the theory of rock failure.

Another feature that bears upon the theory of rock failure is quoted as follows from the thesis by COGAN [1950, p. 41, Fig. 17 and 18]: "Near the Cashin Mine at Paradox, Colorado, a nose of rock of considerable volume is supported by a narrow band of rock underneath. The overlying weight is obviously too great, and the rock is failing by gradual slabbing action."

Figure 5 from page 42 of Cogan's thesis shows the slabbing action at the base of a cliff. The fractures that form the slabs are nearly vertical at the top, curve outwardly in a gentle curve at the bottom, and die at the base of the cliff. A possible explanation of the curved form is that the fractures have formed parallel to the direction of maximum principal stress, and the direction of maximum principal stress changes as the base of the cliff is approached. If this explanation is correct, the rock slabs have been formed as a result of failure in pure tension.

The design and construction of an impact-loading device--A novel technique useful in the study of failure of materials under impact loading has been developed by HESSELBACHER [1949]. The experiments with the impact-loading device have been of a preliminary nature, but it appears that the directions of principal stress at various points in a model can be determined quickly, that

Fig. 6--The impact-loading device

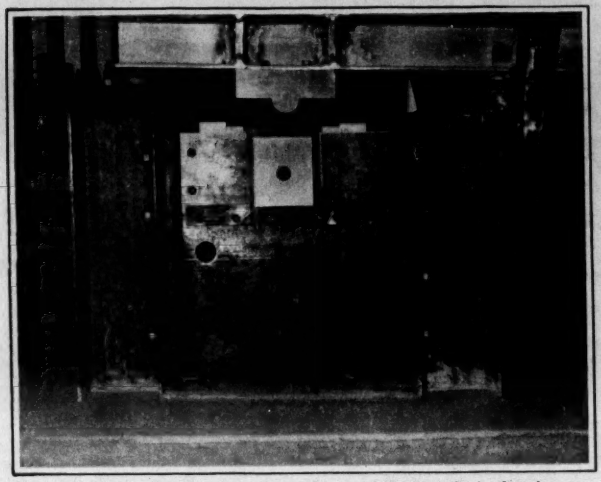


Fig. 7--The laterally restrained model supported within the loading frame

the relative magnitude of an impact load and of a static load to produce a given strain can be determined, that the sequence in which a fracture is formed by pure tension may be observed, and that results obtained by using a polariscope, electronic strain-gages, an interferometer, or mathematical calculations may be compared quickly with failure patterns in brittle lacquer

The apparatus is shown in Figure 6. It consists of an aluminum beam braced laterally and pivoted at one end, a removable tup bolted to the lower flange of the beam at a given distance from the pivot, curved angle irons which function as guides and as a support for the beam, and a steel frame which holds and provides lateral support for the model.

Figure 7 shows details of the steel frame, the manner of positioning the beam to produce an impact load, and the model supported within the steel frame. The upper part of the model has been shaped in the form of the crater of a bomb-burst. The model is constructed of Allite, a photoelastic material. A circular opening has been formed in the model material directly below the crater, and the sides of the model, except for a band around the borders, have been coated with Stresscoat, a brittle lacquer. The model is prevented from lateral expansion by the steel wedges at each side, and is prevented from falling out of the holder by the steel plates that hold the wedges in position. The tup has been machined to the form of a crater, and the model has been centered in the striking position with the wedges. By adjusting the wedges to fit snugly against the sides of the model, but not tightening them, the model is prevented from expanding laterally, and a horizontal load is not induced into the model until the moment of impact.

When the wooden wedge supporting the beam is knocked out, the beam falls in a path that is determined by the pivot and the lateral braces. Wooden wedges may be cut to various lengths to support the beam at predetermined distances above the model, but it is seldom that a drop of over six inches is necessary.

When using the apparatus for applying static loads, an extension is bolted to the aluminum beam in order to clear the concrete base and to obtain a larger mechanical advantage as the load is applied. The same tup used for impact loads, or a tup of different design, whichever is desired for a particular test, may be bolted to the beam.

Laboratory results obtained using the impact-loading device--Quoting from the thesis of HESSELBACHER [1949, pp. 7-9]: "The use of brittle coatings for the indication of strains within

the elastic range was first reported by Dietrich and Lehr of Germany in 1932. Their use was qualitative and pointed out only the areas of greatest strain. The first work on the use of brittle coatings to determine quantitative values was started in 1937 at the Massachusetts Institute of Technology and resulted in the development of the present Stresscoat method. . . The coatings have the property of fracturing at low values of tensile strain (about 0.0007 in. per in.), and in a direction that is always perpendicular to the direction of principal tensile stress in the area of the crack. Brittle coatings will also show larger values of strain by flaking off in a manner similar to the flaking of mill scale on steel. According to deFOREST, ELLIS, and STERN [1942], the flaking occurs in the initial yield region of most metals and correlates directly with the amount of compressive strain present. . . The most sensitive type of flaking Stresscoat will start to flake at a compressive strain of 0.01 in. per in. . . . The compressive stress in the material when flaking starts is only about one-tenth the compressive strength of Allite.

"In the interpretation of results of experiments with Stresscoat, it is generally accepted that the coating will crack when the maximum tensile strain reaches some critical value, but it is also recognized that knowledge of the laws of failure of Stresscoat is incomplete."

Figure 8 shows a model containing a circular opening that was loaded by a drop of 2.75 inches. The sides of the model were confined. The sensitivity of the Stresscoat applied to the model was determined by a calibration test to be 0.0007 in. per in. strain. The strain lines shown in the figure are parallel to the direction of maximum principal stress.

If the area of the model in which cracking has occurred is compared with the stress distribution around a circular opening as computed by Fenner (see Fig. 1a), it may be observed that the strain lines in contact with the opening are present in the tension region at the top and bottom of the opening, but are not present in the compression region. The area containing strain lines at the bottom of the opening is much smaller than the area containing strain lines at the top of the opening.

Figure 9 shows a horseshoe-shaped opening in a model with a large-radius loading-surface. Compression spalling at the sides of the openings indicate compressive strains of at least 0.01 inch per inch in the spalled area. The spalled area is a region of compression, as may be observed from Figures 1a and 8. Horizontal cracks beyond the spalled area and within the region of compression may have formed as a result of one of the following causes: (1) vertical expansion following the release of the impact load; (2) tension strains associated with the wave motion of particles set in vibration in the path of the wave front; or (3) eccentricity of loading causing bending and tension strains on one side of the specimen.

Figure 10 shows a horseshoe-shaped opening in a model loaded statically. The wavy effect is caused by the manner in which the Stresscoat has been applied. The pattern of cracks at the boundary of the opening was produced by a static load of 360 lb applied at the end of the beam. This static load is equivalent to a stress of 533 lb per square inch applied at the load-contact surface of the model. The relative effect of this comparatively large static load and of a relatively small impact load can be observed by comparing the strain area of this figure with that of the preceding figure. The fully-developed strain pattern of Figure 9 was produced by a drop of 2.5 inches measured at the load-contact surface. The kinetic energy of the impact load is 14.75 foot-pounds. Using all the weights available in the laboratory at the time of the experiments, it was impossible to duplicate the impact strain pattern of Figure 9 by static loading. Experiments now in progress are designed to correlate static and impact loads yielding similar strain patterns.

Another point which bears upon the theory of rock failure and which has been observed in these experiments is that failure starts at the boundary of the opening and progresses outwardly into the medium. The points at the ends of the strain lines are called isoentatics. The strain at the ends of the strain lines equals the strain at the beginning of cracking and is determined by a calibration test.

Figure 11 shows a horseshoe-shaped opening in a model with a straight load-contact surface. A drop of 0.65 in. produced the cracks indicated by the inner isoentatics (area 1). The cracks between the inner and outer isoentatics (area 2) were produced by a second impact load falling from a height of 1.25 inches. The random crack pattern was formed during drying of the Stresscoat.

A comparison of interferometer and stresscoat techniques--Figure 12 shows the direction and magnitude of principal stresses produced at various points in the medium surrounding a horseshoe-shaped tunnel opening as determined by PANDYA [1950] using an interferometer of the U. S. Bureau of Reclamation at Denver. The specimen was loaded by a uniform vertical static

Fig. 8--Circular opening, lateral confinement, strain lines produced by drop of 2.75 inches

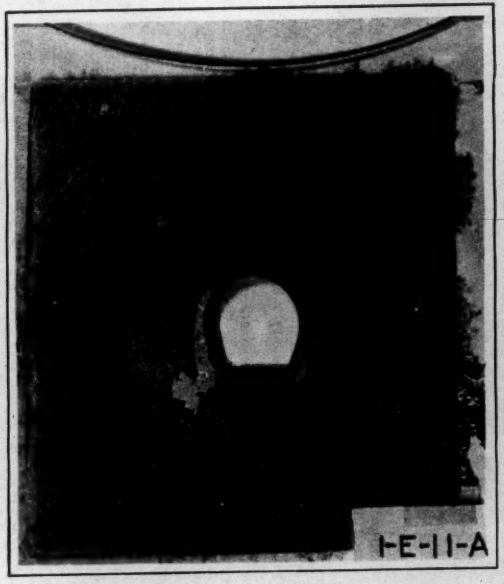


Fig. 9--Horseshoe-shaped opening, lateral confinement, drop 2.5 inches

Fig. 10--Horseshoe-shaped opening, static loading, lateral confinement

Fig. 11--Horseshoe-shaped opening; area 1, drop of 0.55 inch; area 2, drop of 1.25 inches

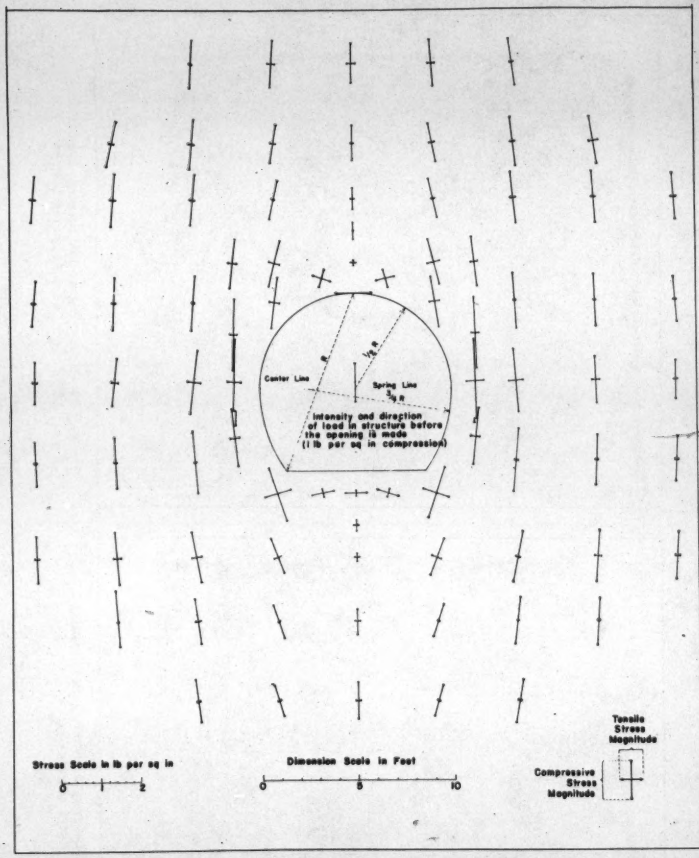


Fig. 12--Photoelastic analysis of stress around a tunnel; tunnel located in infinite plate without lateral confinement; uniform load applied parallel to vertical axis of tunnel; principal stresses and directions

load and was not confined laterally. Figure 13 shows the direction and magnitude of the principal stresses produced in the same model when loaded horizontally and not confined vertically.

The stresses produced by the horizontal and vertical loads might be combined vectorially to obtain the magnitude and direction of the resultant stress at any point for various ratios of the horizontally applied stress and the vertically applied stress.

If the principal stress directions of Figure 12 as determined by Pandya using an interferometer are compared with the principal stress directions of Figure 8 as determined by Hessel-

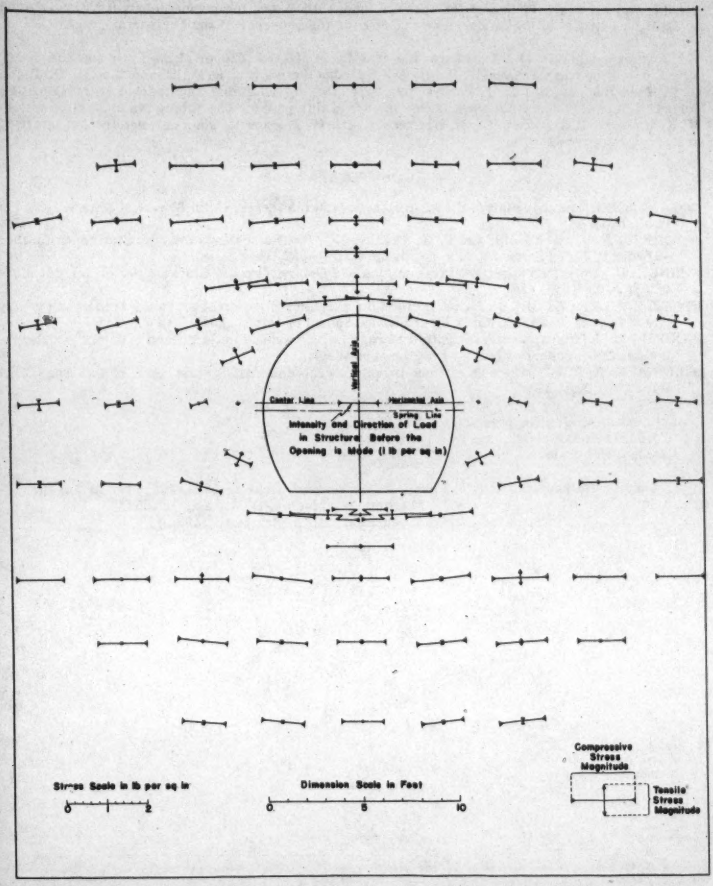


Fig. 13--Photoelastic analysis of stress around a tunnel; tunnel located in infinite plate without lateral confinement; uniform load applied to horizontal axis of tunnel; principal stresses and directions

bacher using Stresscoat, impact loading, and lateral confinement the similarity is immediately apparent. Perhaps if both specimens had been laterally confined, or if the principal stresses resulting from horizontal and vertical loading were combined vectorially, the patterns would be identical.

It appears after comparing the attitude of the horizontal cracks in the compression area of Figure 9 with the principal stress directions obtained with the interferometer in the same area,

that the wave characteristics of the vertical load, rather than the induced horizontal load caused by lateral restraint of the model, may account for the presence of the horizontal cracks.

Acknowledgments--I acknowledge the assistance of E. G. Fisher of the Colorado School of Mines in editing the manuscript. I also acknowledge the work of R. P. Schoemaker, J. P. Cogan, G. E. Hesselbacher, and M. J. Pandya, graduate students in Mining Engineering at the Colorado School of Mines, whose field work is the subject of this paper. The comments and criticism of M. K. Hubbert, B. D. Jones, W. R. McCutchen, and M. J. Pandya, who reviewed the manuscript, are greatly appreciated.

References

COGAN, JOHN, The mechanics of rock failure, Master's thesis, Colo. School of Mines, 1950 (unpublished).

deFOREST, A. V., G. ELLIS, and F. B. STERN, JR., Brittle coatings for quantitative strain measurement, J. Appl. Mech., v. 9, no. 4, pp. A184-A188, 1942.

FENNER, R., Untersuchungen zur Erkenntniss des Gebirgsdrucks, Glückauf, v. 74, pp. 681-695 and pp. 705-715, 1938.

HESSELBACHER, GEORGE, JR., A method for the determination of stresses around an opening under impact loads, Master's thesis, Colo. School of Mines, 1949 (unpublished).

PANDYA, M. J., Stress analysis applied to rock failure around underground openings, Doctor's thesis, Colo. School of Mines, 1950 (unpublished).

SCHOEMAKER, R. P., A review of rock-pressure problems, Amer. Inst. Min. Metal. Eng., Tech. Pub. 2495, Nov. 1948.

Department of Mining Engineering,
Colorado School of Mines,
Golden, Colorado

(Manuscript received May 3, 1950, and, as revised, October 24, 1950; presented at the Thirty-First Annual Meeting, Washington, D. C., May 3, 1950; open for formal discussion until September 1, 1951.)

MAGNETIC WORK OF THE UNITED STATES COAST AND GEODETIC SURVEY FROM JULY 1, 1949 TO JUNE 30, 1950

Elliott B. Roberts

Geomagnetic information is an essential element of navigational charts. It is also required by surveyors in retracing old property lines originally defined by compass bearings. Important collateral uses occur in geophysical exploration for oil-bearing structures, in the study and prediction of radio propagation affecting communications and radio navigational aids, in the study of sunspot activities and of auroral and ionospheric disturbances, and in certain military applications.

The magnetic survey of the United States has required the accumulation, over many years, of observed values of magnetic declination, intensity, and dip at several thousand places in the United States and territorial areas. The declination in the United States, directly needed for navigational and surveying uses, varies from 22° West in Maine to 24° East in the Pacific Northwest. To evaluate the constantly changing components of the magnetic field, repeat observations at a limited number of key stations are made on a regular schedule, whereas continuous readings of the changing components are made at fixed observatories.

During the year, field work was accomplished as indicated in Table 1, and standard observatories were operated at Cheltenham, Maryland; Honolulu, T. H.; San Juan, Puerto Rico; Tucson, Arizona; and Sitka, College, and Barrow, Alaska. Secondary automatic observatories were operated at Gatlinburg, Tennessee, and Logan, Utah, for declination readings.

Table 1--Distribution of magnetic observations from July 1, 1949 to June 30, 1950

Location	Repeat stations				Other stations	Total
	New		Old			
	D, H, I[a]	D	D, H, I	D		
California	..	1	..	1	1	3
Illinois	..	..	..	2	..	2
Kansas	..	..	..	2	..	2
Maine	1	..	4	..	1	6
Maryland	2	..	..	..	..	2
Michigan	..	..	..	2	..	2
Minnesota	..	..	..	1	..	1
Montana	..	..	..	4	..	4
Nevada	..	..	..	1	..	1
New Mexico	..	..	..	1	..	1
New York	..	..	2	..	..	2
North Dakota	..	..	..	2	..	2
Oregon	..	..	..	1	1	2
Rhode Island	..	..	1	..	..	1
South Dakota	..	..	..	2	..	2
Tennessee	..	..	..	1	..	1
Texas	..	..	..	1	..	1
Utah	..	..	..	2	..	2
Vermont	..	1	2	1	..	4
Virginia	1	..	2	..	1	4
Washington	..	..	..	2	2	4
Wyoming	..	..	..	3	..	3
Alaska	..	..	..	..	35	35
Total	4	2	11	29	41	87

[a]D = declination; H = horizontal intensity; I = dip.

A United States central library of world geomagnetic data has been maintained according to law. By solicitation and through exchange agreements, important collections of data have been acquired from world-wide governmental and other scientific agencies, though not from areas under Soviet jurisdiction.

Current revisions of magnetic declination data were made on 312 nautical and aeronautical charts. Revisions of isogonic lines were provided for two such charts. The compilation of a new 1950 Alaska isogonic chart was 75 per cent completed and that of a new 1950 United States isogonic chart was 25 per cent completed.

Four MG-reports, containing scale reproductions of magnetograms, were published, each covering one observatory half-year. The following were also published: Serial 690, Magnetic observations in the American Republics; Serial 717, Magnetic declination in Texas, with isogonic chart of Texas; Serial 718, Magnetic surveys; Serial 726, Magnetic poles and the compass; and Serial 667, United States magnetic tables and charts for 1945.

A noteworthy improvement, saving several man-years per year in processing of magnetic data, was the development of punch-card techniques for the reduction, and preparation for lithographic reproduction, of magnetic observatory results, and likewise for the reduction of the many thousands of magnetic station values required in the compilation of isomagnetic charts. A further improvement in working methods, including the elimination of unnecessary elaborations and the development and simple formulation of new procedures, permitted the establishment of a compact, well-coordinated magnetic cartographic unit, which has functioned with outstanding efficiency.

The development (with the cooperation of the Naval Ordnance Laboratory) of a new induction-type magnetometer, and its successful adaptation to aircraft use by this Bureau, has for the first time offered the close prospect of airborne magnetic surveys of ocean areas and other regions inaccessible by ordinary methods.

Nearly complete progress has been made on the development of a much-needed visible-recording magnetograph for observatory use. A new apparatus has been devised for the drawing of quartz fibers for use in magnetic instruments.

International comparisons of the magnetic standard instruments of Denmark, South Africa, Argentina, and Peru with those of the United States were effected by the exchange and use of special magnetometers owned by the International Union of Geodesy and Geophysics. By participating in this formal program, the Bureau was able to promote greater usefulness of international magnetic readings and better coordination of world magnetic work.

Under an inter-agency agreement, the 1950 isogonic and isoporic world chart, a monumental undertaking involving the use of 78,000 world-wide station values, was compiled on behalf of the Hydrographic Office of the Navy, which will publish this and other scheduled world magnetic charts to be compiled by the Bureau.

In cooperation with the United States Air Force, a field organization has been developed for the performance of airborne magnetic surveys. Flight service is contributed by the Air Force, and the technical planning, direction, observational work, and analysis of results are contributed by this Bureau. Instrumental techniques and flight procedures have been developed, and field operations will be carried out in the succeeding fiscal year.

Revisions of magnetic declination for several thousand places, and isogonic lines for a foreign area, were furnished the Army Map Service, which obtains all needed magnetic data from this Bureau.

Magnetic observatory information has been reported daily to the Central Radio Propagation Laboratory of the National Bureau of Standards for use in the study and prediction of radio transmission conditions.

Cooperation with the Carnegie Institution of Washington included maintenance of the International Magnetic Standard at Cheltenham, of a cosmic-ray station at the same station, and of an atmospheric-electric recorder at Tucson.

Cooperation continued with the Pan American Institute of Geography and History in the establishment of international standards for Western Hemisphere magnetic work. Instruction in such

work was given representatives of Venezuela and Peru, and close collaboration maintained with technical agencies in several countries.

Technical planning and direction were furnished the Inter-American Geodetic Survey for the accomplishment of geomagnetic field surveys in Costa Rica, Cuba, El Salvador, Guatemala, Honduras, Nicaragua, Panama, and Peru. Thirty-four old repeat stations were occupied, and 13 new ones established, for measurement of all magnetic components. Aid was given in the planning and instrumentation of a proposed new observatory in Colombia.

Instruction in geomagnetic work, and aid in the planning of an observatory, were given representatives of the Philippine Islands.

For international use, weekly reports of the K-index, or magnetic activity, were issued for Cheltenham. Throughout the year, collaboration with the International Association of Terrestrial Magnetism and Electricity included the preparation of K-indices, both currently and for the Polar Year 1932-33.

American-manufactured magnetometers and magnetographs were inspected and approved on behalf of the Philippines, the Belgian Congo, New Zealand, Venezuela, and Argentina.

Advice and information regarding instrumental equipment and procedure was given to several foreign governments.

U. S. Coast and Geodetic Survey,
Washington 25, D. C.

(Manuscript received November 21, 1950; presented by title at the Thirty-First Annual Meeting, Washington, D. C., May 2, 1950; open for formal discussion until September 1, 1951.)

DISCUSSION OF

"PEDOLOGICAL RELATIONS OF INFILTRATION PHENOMENA"
by W. O. Smith

[Trans., v. 30, pp. 555-562, 1949]

W. C. Rasmussen (U. S. Geological Survey, Salisbury, Maryland)--Smith provides an illuminating consideration of infiltration through soil in relation to the structure and texture of the soil, its moisture content, and the variation of infiltration for A, B, and C soil zones. The organic nature of soil might also be stressed. Rotting rootlets provide passageways for water in addition to physical structure and texture.

The impression is gained that mechanical treatment, such as plowing and harrowing, generally decreases the infiltration capacity of soil, through destruction of surface structure, and fragmentation. This appears true of the soil in the physical sense. Equally true, in a plowed soil, may be the formation of puddling colloids after a rain, through the breaking of natural granules into fragments. However, the surface infiltration is increased by plowing and harrowing through the turnover of the sod layer composed of grasses and weeds. Smith does not consider the sod layer as a soil zone, yet it is the first barrier that precipitation must pass before it enters the structural crevices and textural pores of the soil. Although a dense sod layer usually does not increase runoff because of its retentive nature, it increases interception, and hence evaporation, so unless the sod is economic, the water is lost anyway.

Moreover, the plant tissues that are turned under rot and provide pore space and permeable channels. Therefore, whether mechanical treatment decreases or increases infiltration capacity depends on an overall view of sod and soil zones, and requires study in each locality. For example, on the Eastern Shore of Maryland, with silty, sandy soils and little colloidal clay, fall plowing apparently increases infiltration by destroying the accumulated mat of intercepting weeds and grasses.

The effect of soluble minerals upon infiltration capacity must also be emphasized. For example, in Caldwell County, Texas, there is a river-terrace formation composed of silt, sand, and gravel, wherein many of the particles are limestone. A black waxy soil is formed at the surface, but caliche banks, composed of semipermeable calcium carbonate, may be found in the A zone, the B zone, or the C zone, depending upon the relation of the surface to the water table. In Bastrop, Robertson, and Brazos Counties, Texas, ferruginous ledges are common in the B zone of the soil formed on many of the glauconitic sandy formations. Needless to say, infiltration is retarded.

Infiltration discussions are still too qualitative and will be reinforced only in the day when reliable measurements are common. The logic of Smith's discussion on infiltration rate as a function of time in a massive soil for a rainfall of constant intensity, as illustrated by his Figure 1, is sound. However, if the graph is based on experimental data, and the experimental points were shown, even though there may be some scatter from the theoretical line, the logic would be almost incontrovertible.

An attempt is being initiated on the Eastern Shore of Maryland to study infiltration by means of a close network of rain gages and observation wells over two watersheds, by applying the hydrologic cycle equation. It is hoped that this will yield quantitative data which will throw more light on the problem of infiltration. As Langbein remarks [discussion, p. 562], geologists are apt to generalize; however, engineers are prone to analyze; it will take a hydrologist to synthesize.

W. O. Smith (U. S. Geological Survey, Washington, D. C., Author's closure)--The term "zonal soil" has a taxonomic and geographical connotation. Zonal soils are such as Tundra, Podzol, Chernozems, Desert Soils, and Laterites. The considerations given in this paper are not necessarily restricted to zonal soils. They apply to any anisotropic soil with a sufficiently strong horizon differentiation. The term "morphological infiltration" is used to denote the penetration of water into individual aggregates or lumps as contrasted with the flow along the voids of the structural porosity. If this use appears confusing, the term "aggregate infiltration" may be used to

describe penetration into true structural aggregates, "fragment infiltration" for penetration into the lumps of a fragmented soil and, finally, "structural infiltration" to denote flow of water down the voids of the structural porosity.

DISCUSSION OF

"EFFECT OF A PARTIAL CUTOFF ON SEEPAGE RATES"
by John S. McNown and En-Yun Hsu

[Trans., v. 31, pp. 468-472, 1950]

Don Kirkham (Iowa State College Experiment Station, Ames, Iowa)--The tables used by the authors for computing the curves in their Figure 3 were those published by Legendre in 1826 (reissued in 1934 by the Biometrika Office, University College, London, through the Cambridge University Press). This is to point out that recently, after nearly a century and a quarter, auxiliary tables to the Legendre Tables have appeared which enable the accurate computation, without undue effort, of the dashed, trend-line portions of the McNown-Hsu curves. The tables in question are "Auxiliary Table of Complete Elliptic Integrals" and "Auxiliary Table for the Incomplete Elliptic Integral," both by E. L. Kaplan and appearing in the Journal of Mathematics and Physics, the first table, in the February 1946 issue (v. 25, pp. 26-36); and the second, in the April 1948 issue (v. 27, pp. 11-36). The second table includes listings of errata in the Legendre tables. With the aid of Kaplan's tables, one finds, taking $n = 1.01$ and $m = 1.000\,000\,75$ in Eq. (5), (6), and (7) of McNown and Hsu, that $L/h = 0.512$, $d/h = 0.977$, and $q/q_0 = 0.120$. If the point corresponding to these values, with a slight correction, to $L/h = 0.500$, is spotted on their Figure 3, it is seen that the trend line for $L/h = 0.5$, as given by the authors, can be extended with very little error, from their value $d/h = 0.73$ to at least $d/h = 0.977$.

The values of q/q_0 read from the authors' Figure 3 are valid, because of symmetry, if the porous flow medium is completely removed from the right or the left of the barrier plane. This idea can be used to determine the best position for a cutoff. Suppose in the authors' Figure 1 that $L/h = 4$ and $d/h = 0.9$, then from their Figure 3, $q/q_0 = 0.63$. Suppose now that the barrier is at the inflow or outflow surface, then one must take $L/h = 8$ and, keeping d/h the same, one finds $q/q_0 = 0.78$. From this example and a little reasoning, one sees that the best position for the cutoff is midway between the inflow and outflow surfaces, a result found in the similar problem of Muskat cited by the authors.

John S. McNown and En-Yun Hsu (Institute of Hydraulic Research, University of Iowa, Iowa City, Iowa, Authors' closure)--The two principal points in Kirkham's discussion are welcome contributions to the study of seepage as affected by partial cutoffs. The writers are glad to learn of the publication of the long-needed expanded tables of elliptic-integral functions. It is good to know that the portions of the curves thought to be approximate in Figure 3 may be taken as reliable.

As the stream lines passing between A and E in Figure 2a are all at right angles to AE, it is evident that the flow pattern would be unchanged by eliminating the portion of the field either to the right or to the left of this line. The writers are indebted to Kirkham for pointing out this additional application of the results presented in the original paper.

A regrettable error in the treatment of the effect of unequal permeabilities in the vertical and horizontal directions was not discovered by the writers until after publication. The equation on page 472 should have been written

$$L'/h = (L/h)\sqrt{K_y/K_x}$$

the radical sign having been omitted. In the subsequent illustration discussed in the same paragraph, the effective length ratio is therefore $2\sqrt{5}$ instead of 2, and the reduction in discharge is eight per cent rather than 18 per cent.

REVIEWS, ABSTRACTS, AND BIBLIOGRAPHY

REVIEWS AND ABSTRACTS

WAHLSTROM, ERNEST E., Theoretical igneous petrology, John Wiley, New York, Chapman and Hall, London, ix + 385 pp., 1950.

This treatise is intended for relatively advanced students who have a working knowledge of petrography and field petrology and who have had at least elementary courses in physics, chemistry, and mathematics. As indicated by the title, the book is largely theoretical; it is built for the most part around pertinent systems whose behavior has been studied in the laboratory and reported in the literature. Descriptions of actual field examples are held to a minimum.

The book consists of two parts and an appendix. Part I consists of four chapters of introductory or background material. After a short introduction (6 pp.), Heterogeneous Equilibrium and the Phase Rule are discussed in chapter 2 (37 pp.). Most of the chapter is devoted to the treatment of idealized two and three component systems. Chapter 3, Equilibrium in Silicate Systems, presents a series of actual silicate systems of petrogenic significance that have been worked out experimentally. Chapter 4 treats the principal groups of igneous minerals very briefly.

Part II is an application of the principles developed in Part I to igneous phenomena and problems, the scope of which can best be indicated by the chapter headings: The Crust and Interior of the Earth; Magmas--Source and Nature; The Ascent and Emplacement of Magmas; Crystallization of Magmas; Igneous Differentiation; Assimilation and Syntexis; Granitization; Late Magmatic and Postmagmatic Processes; Origin of Rock Types; Classification of Igneous Rocks.

The Appendix is entitled Physical-Chemical Concepts useful to Petrologists. The author suggests in the preface that most students should read the appendix before attempting to read the main body of the text. The reviewer is of the opinion that if the student does not already possess a knowledge of elementary physical chemistry perusal of the appendix will not help him a great deal. It covers just over 13 pages and consists almost entirely of definitions and equations such as might be found in a handbook of chemistry and physics. There is very little discussion and no examples are given to clarify the definitions or to show how the equations are used or what they mean. Moreover, some of the definitions and discussions are incomplete or inaccurate. For example, in the discussion of Van der Waals' Equation on pages 334-335 the second assumption that must be made in applying the ideal gas law, that the molecules have no significant volume, is not mentioned. The equation is correctly given, but there is no indication of what the constants a and b mean. If one has to go to a handbook for the significance and values of the constants he might as well get the equation from the handbook also. Similarly, no units are given for the terms in the equation for the coefficient of viscosity on page 339. The definition of a saturated solution on page 343 is not general or accurate because it does not mention equilibrium with a solid phase. Neither is the definition of a supersaturated solution (p. 343) accurate nor general, because it fails to take into account retrograde solubility. The definition of the average calorie (p. 344) is in error by a factor of 100. The definition of solid solution (p. 344) is more general than the one commonly employed by mineralogists and leaves the impression that it has nothing to do with crystal structure. It appears to the reviewer that the appendix should either have been expanded very considerably and illustrative examples added to make it useful to a student who has had no physical chemistry, or left out entirely.

This same brevity characterizes some of the discussions in the main part of the text. It is highly desirable to have a textbook as concise as is compatible with clarity. When treatment of a topic is so abbreviated, however, as to leave students confused, discussion of that topic might better have been omitted and reference made to adequate treatment elsewhere. The treatment of the phase rule on pages 9-10 is exceedingly brief and no example is given to clarify the meaning of degrees of freedom. In general the discussion of phase equilibrium diagrams is clear and straightforward. In places, however, it is too condensed for the average student to follow readily; for example, the description of areas in the system albite-diopside-anorthite at the bottom of

page 36, and the use of the term "three-phase boundaries" on the following pages with no explanation of what the term means or why the boundaries are so named. The discussion of Figure 9 on pages 55-56 would have been helped by following the course of crystallization of at least one liquid. To be sure, this is done in the discussion of the idealized diagram of a similar system on page 22, but a student will understand and remember an example involving actual minerals much better than one with "components A and B." Only 15 pages are devoted to the history, principles, and systems of classification of igneous rocks.

Several outmoded ideas have crept into the text. For example, the idea expressed in the last paragraph on page 150 that (compounds of) halogens predominate in the initial stages of an eruption and that sulfur exhalations appear in the late stages of eruptive activity now appears to be without foundation. In this same paragraph it is stated that "solid substances condense . . . about vents and fumaroles." It is now generally accepted that most, if not all, of these substances do not condense from vapor of their composition, but are deposited from solutions as they come to the surface from regions of higher temperature and pressure where the predominant water could hold non-volatile material in solutions even though the water is not liquid. On pages 184 and 225 thin rhyolite flows of considerable extent are mentioned as having formed from lava "as fluid as basaltic lava." Many of these supposed flows have been re-studied in recent years and, so far as the reviewer is aware, they have uniformly proven to be not flows, but welded tuffs. On page 272 the old idea that pegmatites have crystallized in the neighborhood of 575° C is stated again in spite of the fact that it has been rejected by its author and discredited by recent experimental work.

There are a number of errors in fact and statement in the book. For example, on page 29, line 4 from the bottom it is stated that "the only solid that will appear on cooling is solid A" (from a liquid in the field of A in a ternary system). "Only" should read "first", because further cooling will cause other solids to appear. On pages 119 and 120 it is stated that pallasites consist almost entirely of olivine, whereas actually they contain less olivine than chondrodites do, and contain approximately 50 per cent nickel-iron. The statement on page 151 that Shepherd found volcanic rocks commonly to yield 5 to 6 cc of gas per gram is misleading, because Shepherd's paper reports variations from 0.69 to 214.8 cc for individual lavas. The variation is less extreme for intrusive rocks (29 to 89 cc) but is much greater than would be inferred from Wahlstrom's statement that it "was near 30 cc per gram for many samples." The diagrams on page 179 imply that lava, cinder, and composite cones have about the same slopes which, of course, is far from the case. On page 278 chrysotile and asbestos are mentioned as separate minerals whereas asbestos is a variety of chrysotile. In the discussion of lamprophyres (p. 309) it is stated, "The dark minerals commonly appear as phenocrysts, but whether in phenocrysts or groundmass . . ." This implies that the dark minerals occur either one place or the other, whereas one of the most striking and characteristic properties of lamprophyres is that the ferromagnesian minerals occur both as phenocrysts and in the groundmass. Failure to recognize this characteristic has caused more than one geologist to go astray in certain geologic interpretations recently. The terms "burning gases" (p. 182), "acidic rocks" (p.183), "deuteric" (pp. 274-288), and "siliceous" (p. 295) appear to be used erroneously.

In any textbook of this nature there are inevitably many statements on which opinions differ. There is no point to discussing these in a review, and very little point to discussing many of them anywhere else. At first glance the final paragraph on page 267 appears to be such a case. Actually it is a complete misinterpretation of the statement by Morey and Ingerson, who had no intention of implying that water above its critical temperature is not important in geologic processes, as Wahlstrom's discussion indicates. Actually Ingerson had earlier (Econ. Geol., v. 39, p. 454, 1934) emphasized the very points made here; in Wahlstrom's words (1) ". . . whether the water solvent is in the liquid or gaseous state is inconsequential . . ." and (2) "The solubility . . . in supercritical water vapor is a function of pressure . . ." The 1934 paper made another point in this connection, that, at a given pressure, temperature is important in determining solubility.

There are numerous typographical errors throughout the work. Most of these are obvious and require no comment. There are a few, however, that should be mentioned. On page 94, paragraph 3, line 2, "magnesium" should read "magnesian." On page 106 the equatorial radius of the Earth should be given as 6378.388 km instead of 5378.388 km. On page 136, line 3, "crystal" should read "crustal." Page 217, paragraph 3, line 13, "intramolecular" should read "intermolecular." Under the References on page 330 a well-known textbook of petrology is listed as a Textbook of Pathology.

Theoretical Igneous Petrology is a very concise treatment of the subject. The illustrations, both diagrams (146) and photographs (9), are clear, well chosen, and excellently reproduced. There

is a real need for a thorough textbook on theoretical petrology. The book under review attempts to fill this need and, although it falls short of the goal for reasons outlined above, its coverage of the subject matter is such that it can serve as a very useful guide for such a course. Classroom expansion and outside reading are necessary for a well-rounded course in petrology, of course, no matter what textbook is used. The lists of references after the individual chapters in this book should prove helpful in selecting these collateral reading assignments.

EARL INGERSON

BIBLIOGRAPHY

BIBLIOGRAPHY: GENERAL

FESSENKOV, V. G., On the gaseous tail of the Earth, Astron. J., USSR, v. 27, no. 2, 1950 (in Russian), English abstr. in Astron. News Letter (Harvard), v. 51, pp. 8-9, 1950 [abstr. in Phys. Abst., v. 54, no. 637, p. 3, 1951].

HAALCK, HANS, Die vollständige Bestimmung örtlicher gravimetrischer Störungsfelder aus Drehwaagemessungen mit Berechnungsbeispiel, Veröff. Geod. Inst., Potsdam, no. 4, pp. 1-41, 1950.

HAALCK, HANS, Das physikalische Bildungsgesetz der Figur der Erde (Theorie der normalen Erdgestalt), Veröff. Geod. Inst., Potsdam, no. 4, pp. 43-53, 1950.

LATIMER, W. M , Astrochemical problems in the formation of the Earth, Science, v. 112, pp. 101-104, July 28, 1950 [abstr. in Chem. Abst., v. 53, no. 636, p. 1048, 1950].

LOZANO CALVO, LUIS, Las necesidades cartográficas de las medidas de gravedad, Rev. Geofís., Madrid, v. 9, no. 34, pp. 113-122, 1950 (summary in English).

MARBLE, JOHN PUTNAM (chairman), Report of the Committee on the Measurement of Geologic Time, 1949-1950, Div. Geol. Geog., Nat. Res. Coun., 118 pp., 1950 (processed).

MOORE, R. WOODWARD, Geophysical methods of subsurface exploration in highway construction, Publ. Roads, v. 26, no. 3, pp. 49-64, 1950 [abstr. in Appl. Mech. Rev., v. 4, no. 1, p. 67, 1951].

NICOLIN, T., Indication of a correspondence between geophysical phenomena and the motion of the pole, Atti. Acad. Naz. Lincei, v. 8, pp. 348-355, 1950 (in Italian) [abstr. in Phys. Abst., v. 53, no. 635, p. 885, 1950].

PAN AMERICAN INSTITUTE OF GEOGRAPHY AND HISTORY, 13 Bulletins of Information, relative to the Fifth General Assembly, Santiago, Chile, about 300 pp., 1950 (in Spanish) (processed). [Contains information concerning delegates, program, and incidental matters.]

RUTHE, KURT, Nordpolargebiet, Polarforschung, v. 2, no. 1-2, pp. 298-311, 1949.

RUTHE, KURT, Südpolargebiet, Polarforschung, v. 2, no. 1-2, pp. 311-316, 1949.

SHEPARD, E. RAYMOND, Subsurface explorations by geophysical methods, Proc. Amer. Soc. Test. Mat., v. 49, pp. 993-1015, 1949 [abstr. in Appl. Mech. Rev., v. 4, no. 1, p. 67, 1951].

TÁRCZY-HORNOCH, A., Geophysics in the service of mining, Hungarian J. Min. Metal., v. 5, no. 2-3, pp. 75-90, 1950.

BIBLIOGRAPHY: GEODESY

ALLER, R. M., Coordenadas del Observatorio de la Universidad de Santiago, Urania, v. 35, no. 221-222, pp. 10-20, 1950.

ALSINA FUERTES, F., La deflexión gravitatoria de la luz y el principio de equivalencia, An. Soc. Cient. Argentina, v. 150, pp. 213-222, 1950.

BEER, M., Measurements of gravity in the Canadian Arctic and Greenland, Dominion Obs., Canada, Contrib., v. 1, no. 5, 9 pp., 1950.

BERROTH, A., Complementäre physikalische Höhen, mit einer Anwendung auf die Schweizer Alpen, Gerlands Beitr. Geophysik, v. 61, no. 3, pp. 184-194, 1950.

BOAGA, G., La geodesia di fronte ai progressi della tecnica, Riv. Catast. Serv. tec. erariali, Italy, v. 4, no. 3, pp. 163-176, 1949.

BOGDANOV, A. A., B. L. GUREVICH, and S. I. SHERESHEVSKAIA, Anomalies in gravitational force and their connection with the primary tectonic elements of the eastern regions of the Ukrainian SSR, Izvestia Serlia geograficheskaia i geofizicheskaia, Akad. Nauk, v. 14, no. 3, pp. 223-231, May-June 1950 (in Russian).

CAGNIARD, L., A. GLODEN, and M. LUCIUS, Rapport sur une campagne gravimétrique effectuée au Grand Duché de Luxembourg en Octobre 1948, Ciel et Terre, Belg., v. 65, pp. 215-218, 1949.

CHEBOTAREV, A. S., Geodeziia, Izd-vo geodezicheskoi i Kartografii, Moskva, pt. 2, 636 pp., 1949.

COOK, A. H., Measurements of gravity in Ireland, Dublin Inst. Advanced Studies, Geophys. Mem., no. 2, pt. 1, 28 pp., 1950.

DE CASTRO, H., Variation of gravity with time due to the influence of the Moon and the Sun, Ciencia, Mexico, v. 10, no. 1-2, pp. 29-40, 1950 [abstr. in Phys. Abst., v. 53, no. 636, p. 1047, 1950].

EVTEEV, O. A., Pervye russkie geodezisty na Tikhom okeane, Gos. izd-vo geogr. lit-ry, Moskva, 105 pp., 1950.

GARLAND, G. D., Interpretations of gravimetric and magnetic anomalies on traverses in the Canadian shield in northern Ontario, Dominion Obs., Canada, Pub., v. 16, no. 1, 57 pp., 1950.

GILVARRY, J. J., S. H. BROWNE, and I. K. WILLIAMS, Theory of blind navigation by dynamical measurements, J. Appl. Phys., v. 21, pp. 753-761, Aug. 1950 [abstr. in Phys. Abstr., v. 53, p. 795, 1950].

HAGIWARA, T., T. RIKITAKE, K. KASAHARA, and J. YAMADA, Observations of the deformation of the Earth's surface at Aburatsubo, Miura Peninsula, pts. 2 and 3, Bull. Earthquake Res. Inst., Tokyo Univ., v. 27, pp. 35-44, 1949.

HATTORI, TADAHIKO, On the periodic components of latitude variation, Japanese J. Astron., v. 1, no. 1, pp. 87-97, 1949.

MacDONALD, K. W., Shoran operations, Canadian Surveyor, v. 10, no. 7, pp. 16-20, 1951.

MUNK, W. H., and R. L. MILLER, Variation in the Earth's angular velocity resulting from fluctuations in atmospheric and oceanic circulation, Tellus, v. 2, pp. 93-101, 1950.

NABOKOV, MIKHAIL E., Astronomicheskie nabliudeniia s binoklem, Gos. izd-vo tekhn.-teoret. lit-ry, 182 pp., 1948.

PAROLI, A., Un particolare procedimento per determinare l'errore medio di posizione d'un sistema di punti, Riv. Catast. Serv. tec. erariali, Italy, v. 4, no. 3, pp. 184-188, 1949.

ROSS, J. E. R , Shoran control, Canadian Surveyor, v. 10, no. 7, pp. 10-15, 1951.

SPENCE, H. N., Helicopter operation, Knob Lake vicinity, Canadian Surveyor, v. 10, no. 7, pp. 2-8, 1951.

WARNER, J., The application of radar to surveying, Emp. Surv. Rev., v. 10, no. 78, pp. 338-348, 1950.

WEIKEN, K., Ergebnisse der Pendelmessungen der Jahre 1934 bis 1943, Veröff. Geod. Inst., no. 3, Potsdam, 31 pp., 1950.

BIBLIOGRAPHY: SEISMOLOGY

CALOI, P., L. MARCELLI, and G. PANNOCCHIA, Sulla velocità di propagazione delle onde superficiali in corrispondenza dell'Atlantico, An. Geofis., v. 2, pp. 347-356, 1949.

DI FILIPPO, DOMENICO, Il terremoto delle Azzore del 25 Novembre 1941, An. Geofis., v. 2, pp. 400-405, 1949.

DI FILIPPO, DOMENICO, L'onda "G" di Gutenberg nel terremoto delle Azzore del 25 Novembre 1941, An. Geofis., v. 3, pp. 39-45, 1950.

DI FILIPPO, D., and L. MARCELLI, La "magnitudo" dei terremoti e la sua determinazione nella stazione sismica di Roma, An. Geofis., v. 2, pp. 486-492, 1949.

DI FILIPPO, D., and L. MARCELLI, Sul movimento iniziale delle onde sismiche registrate a Roma durante il periodo 1938-1943, An. Geofis., v. 2, pp. 589-606, 1949.

DI FILIPPO, D., and L. MARCELLI, Magnitudo ed energia dei terremoti in Italia, An. Geofis., v. 3, pp. 337-348, 1950.

INGLADA GARCIA-SERRANO, V., Macroseismic methods of focal depth determination, Rev. Geofis., v. 9, pp. 123-126, 1950 (in Spanish) [abstr. in Phys. Abst., v. 54, no. 637, p. 85, 1951].

LONGUET-HIGGINS, M. S., A theory of the origin of microseisms, Phil. Trans. A, no. 857, pp. 1-35, 1950 [abstr. in Phys. Abst., v. 53, no. 636, p. 1048, 1950].

NAKAMURA, SAEMON TARO, On visco-elastic medium, pt. 3, Sci. Rep., Tôhoku Univ., v. 2, no. 2, pp. 146-148, 1950.

ZÁTOPEK, A., Dynamical magnification of a seismograph excited by a shock of the form $\lambda^n \cdot e^{-\lambda\tau}\tau^n$, Čas. Pěst. Mat. Fis., v. 75, no. 2, pp. 103-111, 1950 (in Czechoslovakian) [abstr. in Phys. Abst., v. 53, no. 636, p. 1047, 1950].

BIBLIOGRAPHY: METEOROLOGY

ARAKAWA, H., Transformation of the equations of motion in dynamical meteorology to orthogonal curvilinear coordinates, Papers in Met. Geophys., Met. Res. Inst., Tokyo, v. 1, no. 1, pp. 45-49, 1950.

ARIZUMI, N., A diagrammatic method of computing vertical motion in the atmosphere and its applications, Geophys. Mag., Centr. Met. Obs., Tokyo, v. 22, no. 2, pp. 131-141, 1950.

BERLYAND, M. E., On the variation in time of the temperature in the surface layer of the atmosphere, Doklady Akad. SSSR (n. s.), v. 67, pp. 1017-1020, 1949 (in Russian) [abstr. in Appl. Mech. Rev., v. 4, no. 1, p. 69, 1951].

BERSON, F. A., On the factors controlling the instability of long waves in zonal currents, Arkiv för Geofys., Stockholm, v. 1, no. 9, pp. 187-236, 1950.

BERSON, F. A., On the role of long-wave instability in the general circulation, A study of five-day means in November 1948, Med. Swedish Met. Hydrolog. Inst., Ser. A, no. 3, 13 pp., 1950.

BEST, A. C , Empirical formulae for the terminal velocity of water drops falling through the atmosphere, Q. J. R. Met. Soc., v. 76, pp. 302-311, 1950 [abstr. in Phys. Abst., v. 53, no. 635, p. 961, 1950].

BOSSY, L., and R. PASTIELS, Étude des propriétés fondamentales des actinomètres, Inst. R. Met. Belgique, v. 29, 116 pp., 1948.

BROADBENT, L., The microclimate of the potato crop, Q. J. R. Met. Soc., v. 76, no. 330, pp. 439-454, 1950.

BURKE, T., and J. J. NOLAN, Observations on the radium A content of the atmosphere, Proc. R. Irish Acad., v. 53A, pp. 145-161, July, 1950 [abstr. in Phys. Abst., v. 53, no. 636, p. 1049, 1950].

CHACKETT, K. F., F. A. PANETH, and E. J. WILSON, Chemical analysis of stratosphere samples from 50 and 70 km height, J. Atmos. Terr. Phys., v. 1, no. 1, pp. 49-55, 1950 [abstr. in Phys. Abst., v. 53, no. 636, p. 1049, 1950].

CRABB, GEORGE A., JR., Solar radiation investigations in Michigan, Mich. Agric. Exp. Sta., Tech. Bull. 222, 153 pp., 1950.

CROWE, P. R., Rainfall regime in the south-eastern United States, London Essays in Geogr., London Sch. of Econ. and Political Sci., Univ. of London, Harvard Univ. Press., pp. 71-90, 1951.

DUFOUR, L., Esquisse d'une histoire de la météorologie en Belgique, Inst. R. Mét., Belgique, Misc., v. 40, 55 pp., 1950.

ELIASSEN, A., The quasi-static equations of motion with pressure as independent variable, Geofys. Pub., v. 17, no. 3, 40 pp., 1950 [abstr. in Phys. Abst., v. 53, no. 635, p. 960, 1950].

ERTEL, H., A method of approximate calculation for air mass transfer, S. B. Deutsch. Akad. Wiss. Berlin, Math.-nat. Kl., no. 3, 23 pp., 1948 (in German) [abstr. in Phys. Abst., v. 53, no. 634, p. 872, 1950].

EUWE, W., Forecasting rainfall in the period December-January-February for Java and Madura, Met. Geophys. Dienst Kon. Mag. Met. Obs., Batavia, Verhandelingen 39, 16 pp., 1949.

FALCKENBERG, G., and E. LAUTER, The ionization of the stratosphere above tropospheric high and low pressure regions, Zs. Met., v. 3, pp. 136-140, 1950 (in German) [abstr. in Phys. Abst., v. 53, no. 634, p. 876, 1950].

FLOHN, HERMANN, Berichte des Deutschen Wetterdienst in der U. S. Zone, Deuts. Wetterdienst, U. S. Zone, Bad Kissingen, no. 18, 52 pp., 1950 (summary in English).

GODSON, W. L., A study of the deviations of wind speeds and directions from geostrophic values, Q. J. R. Met. Soc., v. 72, pp. 3-15, 1950 [abstr. in Appl. Mech. Rev., v. 3, no. 11, p. 389, 1950].

GUTMAN, L. N., On the theory of mountain-valley winds, Dokl. Akad. Nauk SSSR, v. 66, no. 2, pp. 199-202, 1949 (in Russian) [abstr. in Appl. Mech. Rev., v. 3, no. 9, p. 287, 1950].

HARE, F. KENNETH, Climatic classification, London Essays in Geogr., London Sch. of Econ. and Political Sci., Univ. of London, Harvard Univ. Press, pp. 111-134, 1951.

HARTLEY, G. E. W., The development of electrical anomometers, Inst. Elect. Engr., Paper 1063, 8 pp., 1951 [abstr. in Phys. Abst., v. 54, no. 637, p. 86, 1951].

HÖGBERG, L., Lufttrycket i Sverige 1901-1930 (Atmospheric pressure in Sweden), Med. Swedish Met. Hydrolog. Inst., Ser. A, No. 2, 20 pp. + 4 pl., 1950 (summary in English).

HOLDER, ERNST, The differential equation for the stream function of the steady rotationally symmetrical circulation of an adiabatically varying frictionless atmosphere over the Earth, Met. Rundsch., v. 1, pp. 449-450, 1948 (in German) [abstr. in Appl. Mech. Rev., v. 3, no. 11, p. 390, 1950].

ICHIE, TAKASHI, On the wave caused by an oscillating pressure, J. Oceanogr. Soc. Japan, pp. 1-18, 1949 (in Japanese) [abstr. in Appl. Mech. Rev., v. 3, no. 11, p. 390, 1950].

ISHIMARU, Y., Cloud and upper air current observations during the Second International Polar Year (July 1932 to August 1933) at Haneda Weather Station in Tokyo Air Port, Geophys. Mag., Tokyo, v. 22, no. 2, pp. 157-175, 1950.

JANSÁ GUARDIOLA, JOSÉ M., El sondeo horizontal y el diagrama sinóptico espacio-temporal, Rev. Geofís., v. 9, no. 35, pp. 234-247, 1950.

JUNGE, CHRISTIAN, Zur Anwendung des Richardson'schen Kriteriums in der freien Atmosphäre, An. Met., v. 3, no. 9-10, pp. 298-301, 1950 (summary in English).

KAMAMOTO, H., and S. KIMURA, Wind-direction and speed robot, Papers in Met. Geophys., Met. Res. Inst., Tokyo, v. 1, no. 1, pp. 77-80, 1950.

KANO, KYOICHI, On Richardson's criterion concerning the increase or decrease of turbulent energy in the free atmosphere, J. Met. Soc., Japan, v. 27, no. 10, pp. 311-318, 1949 (in Japanese) [abstr. in Appl. Mech. Rev., v. 4, no. 1, p. 69, 1951].

KAWABATA, Y., and M. FUJITO, Distribution of total horizontal insolation in Japan and its neighbourhood, Geophys. Mag., Tokyo, v. 22, no. 2, pp. 143-155, 1950.

KESAVAMURTHY, A., and S. P. VENKITESHWARAN, A distant reading electronic anemometer and a selsyn operated wind vane, Indian J. Met. Geophys., v. 1, pp. 199-206, 1950 [abstr. in Phys. Abst., v. 53, no. 636, p. 1049, 1950].

KOSIBA, ALEKSANDER, Zagadnienie Współczesnych Oscylacji Klimatycznych (Climatic oscillations in Central Europe), Czasopisma Geograf., v. 20, no. 1-4, pp. 31-58, 1949 (summary in English).

KOSIBA, ALEKSANDER, Niektóre Zagadnienia Ogólnej Cyrkulacji Atmosferycznej (Atmospheric circulation in the zone of the Westerlies), Czasopisma Geograf., v. 20, no. 1-4, pp. 59-80, 1949 (summary in English).

LAHAYE, EDMOND, Contribution à la résolution des équations du mouvement d'un fluide et des équations de la circulation atmosphérique générale, Inst. R. Mét., Belgique, Mem., v. 38, 78 pp., 1950.

LANGFORD, J. C., Southern ocean analysis--some aspects, Weather Development and Res. Bull. 16, Commonwealth Met. Bur., Australia, pp. 5-31 + 11 pl., 1950 (processed).

LILJEQUIST, G. H., On fluctuations of the summer mean temperature in Sweden, Sver. Met. Hydrolog. Inst., Ser. B, No. 7, 24 pp., 1950.

MAGATA, M., Dynamics of the eye of storm, Papers in Met. Geophys., Met. Res. Inst., Tokyo, v. 1, no. 1, pp. 29-37, 1950.

MAGATA, M., Dynamics of the movement of atmospheric vortices, Papers in Met. Geophys., Met. Res. Inst., Tokyo, v. 1, no. 1, pp. 38-44, 1950.

MANNING, L. A., O. G. VILLARD, JR., and A. M. PETERSON, Meteoric echo study of upper atmosphere winds, Proc. Inst. Radio Eng., v. 38, pp. 877-883, 1950 [abstr. in Phys. Abst., v. 54, no. 637, p. 86, 1951].

MEETHAM, A. R., Natural removal of pollution from the atmosphere, Q. J. R. Met. Soc., v. 76, no. 330, pp. 359-371 + 2 pl., 1950.

METZLER, KARL, Das Raumklima unter besonderer Berücksichtigung der Süd- und Westseite, An. Met., v. 3, no. 9-10, pp. 291-297, 1950 (summary in English).

MILNES, B , and R. S. UNWIN, A radio meteorological investigation in the south island of New Zealand, Proc. Phys. Soc., London B, v. 63, pp. 595-616, 1950 [abstr. in Phys. Abst., v. 53, no. 635, p. 962, 1950].

MIYAKE, Y., and K. SARUHASHI, The variation of the ultraviolet solar radiation during the eclipse, Geophys. Mag., Tokyo, v. 22, no. 1, pp. 5-9, 1950.

MIYAKE, Y., and Y. SUGIURA, A study on nitrogen compounds in the atmosphere, Geophys. Mag., Tokyo, v. 22, no. 1, pp. 1-4, 1950.

MUNRO, G. H., Travelling disturbances in the ionosphere, Proc. R. Soc. A, v. 202, pp. 208-223, 1950 [abstr. in Phys. Abst., v. 53, no. 634, p. 873, 1950].

NAKADA, Y., Long-range forecasting by periodicity extrapolation method (Preliminary Report), Geophys. Mag., Tokyo, v. 22, no. 2, pp. 99-108, 1950.

NAKAMURA, SAEMON TARO, Some meteorological statistics; pt. 1, Cloudy and fine days means, Sci. Rep., Tôhoku Univ., v. 2, no. 2, pp. 107-138, 1950.

NICOLET, M., and R. DOGNIAUX, Ensoleillement et orientation en Belgique, pt. 3, Étude de l'effet des conditions atmosphériques, Inst. R. Mét., Belgique, Mém., v. 40, 53 pp. + 3 pl., 1950.

NOLAN, P. J., and D. J. DOHERTY, Size and charge distribution of atmospheric condensation nuclei, Proc. R. Irish Acad., v. 53A, pp. 163-179, 1950 [abstr. in Phys. Abst., v. 53, no. 636, p. 1050, 1950].

NYBERG, ALF, An aerological study of large-scale atmospheric disturbances, Tellus, v. 1, pp. 44-53, 1949 [abstr. in Appl. Mech. Rev., v. 3, no. 11, p. 390, 1950].

PALOMARES, MANUEL, La convergencia por rozamiento y las corrientes verticales en España, Rev. Geofís., Madrid, v. 9, no. 34, pp. 147-165 + 5 pl., 1950 (summary in English).

PASQUILL, F., Some further considerations of the measurement and indirect evaluation of natural evaporation, Q. J. R. Met. Soc., v. 76, pp. 287-301, 1950 [abstr. in Phys. Abst., v. 53, no. 635, p. 960, 1950].

POLLI, SILVIO, Cento anni di osservazioni meteorologiche eseguite a Trieste (1841-1940); pt. 5, La direzione del vento, Boll. Soc. Adriatica di Scienze Naturali, Trieste, v. 45, pp. 31-58, 1950.

POLLI, SILVIO, Osservazioni meteoriche esesguite a Trieste nel 1948, Inst. Talassografico, Trieste, Pub. 259, 19 pp., 1950.

RAAB, LARS, A direct indicating anemometer, Arkiv för Geofysik, Kungl. Svenska Vetenskap., v. 1, no. 5, pp. 117-121, 1950.

RICHARDSON, E. G., The fine structure of atmospheric turbulence in relation to the propagation of sound over the ground, Proc. R. Soc., Ser. A, v. 203, pp. 149-164, Sept. 22, 1950 [abstr. in Phys. Abst., v. 53, no. 636, p. 1050, 1950].

RIEHL, H., A model of hurricane formation, J. Appl. Phys., v. 21, pp. 917-925, 1950 [abstr. in Phys. Abst., v. 53, no. 636, p. 1050, 1950].

RODEWALD, MARTIN, Zur Frage der Luftdruckverhältnisse in der Arktis, An. Met., v. 3, no. 9-10, pp. 284-290, 1950 (summary in English).

ROSENBROCK, H. H., and J. R. TAGG, Wind- and gust-measuring instruments developed for a wind-power survey, Inst. Elect. Engrs., Paper 1065, 10 pp., 1951 [abstr. in Phys. Abst., v. 54, no. 637, p. 86, 1951].

SANSON, ..., La sécheresse remarquable de la période 1941-1949 en France, La Houille Blanche, v. 2, no. 2, p. 122, 1950.

SANUKI, M., Studies on biplane wind vanes, ventilator tubes and cup anemometers, pt. 1, Papers in Met. Geophys., Met. Res. Inst., Tokyo, v. 1, no. 1, pp. 81-132, 1950.

SATO, TAKAO, Researches on the mathematical insolation due to direct Sun during any period, Sci. Rep., Tôhoku Univ., v. 2, no. 2, pp. 86-106, 1950.

SCHAEFER, V. J., Experimental meteorology, Zs. angew. Math. Phys., v. 1, pp. 153-184 and 217-236, 1950 [abstr. in Phys. Abst., v. 53, no. 634, p. 874, 1950].

SCHMIDT, F. H., On the distribution of duration of sunshine in Java, Verhand. 40, Kementerian Perhubungan, Tenaga dan Pekerdjaan Umum Djawatan Meterologi dan Geofisik, Kjakarta, Indonesia, 18 pp. + 9 maps, 1950.

SEKIGUTI, T., Introduction to local climatology, Geophys. Mag., Tokyo, v. 22, no. 1, pp. 29-33, 1950.

SEKIGUTI, T., Rural houses and prevailing winds, local climatological study of the Akaho Fan, Kami-Ina, Papers in Met. Geophys., Met. Res. Inst., Tokyo, v. 1, no. 1, pp. 67-76, 1950.

SEKIHARA, K., and K. KAWAMURA, A study of the distribution of ultraviolet sky radiation, Geophys. Mag., Tokyo, v. 22, no. 1, pp. 21-28, 1950.

SIOTANI, MASAO, and G. YAMAMOTO, Atmospheric turbulence over a large city, I, II, J. Met. Soc. Japan, v. 27, pp. 67-77 and 111-115, 1949 (in Japanese) [abstr. in Appl. Mech. Rev., v. 3, no. 12, p. 432, 1950].

SOCIÉTÉ MÉTÉOROLOGIE DE FRANCE, Bibliographie Météorologique Internationale, Paris, v. 4, 244 pp., 1948.

TAJIMA, S., On the meridional oscillation of anticyclone of horse latitudes in Japan and its effect on the weather, Geophys. Mag., Tokyo, v. 22, no. 2, pp. 109-130, 1950.

TAKEDA, KYOICHI, The vertical distribution of wind velocity near the Earth's surface, J. Met. Soc. Japan, v. 27, pp. 333-341 and 363-370, 1949 (in Japanese) [abstr. in Appl. Mech. Rev., v. 3, no. 12, p. 432, 1950].

TIOTANI, MASAO, and GITTI YAMAMOTO, Atmospheric turbulence near the ground, pt. 1 and 2, J. Met. Soc. Japan, v. 27, pp. 73-77 and 219-224, 1949 (in Japanese) [abstr. in Appl. Mech. Rev., v. 3, no. 12, p. 432, 1950].

TROJER, HANS, Ein Beitrag zu einer dynamischen Klimatologie, Urania, No. 220, 18 pp., 1949 (in German and Spanish).

TSUJI, M , On the rate of evaporation and condensation of falling drops, Geophys. Mag., Tokyo, v. 22, no. 1, pp. 11-14, 1950.

VAN MIEGHEM, JACQUES, L'équation aux dérivées partielles de la pression de perturbation associée aux ondulations de grande longueur d'onde du courant géostrophique zonal, Inst. R. Mét., Belgique, Mém., v. 39, 45 pp., 1950.

VISHER, STEPHEN S., Indiana thunderstorms, Proc. Ind. Academy of Science, v. 59, pp. 255-257, 1950.

VON KILINSKI, E., On the influence of meteorological factors on atmospheric conductivity, Zs. Met., v. 3, pp. 46-49, 1949 (in German) [abstr. in Phys. Abst., v. 53, no. 634, 1950].

WAGEMANN, HELLMUT, Horizontale Schwingungen der Erdatmosphäre und die stationäre Luftdruckverteilung in gemässigten Breiten, An. Met., v. 3, no. 9-10, pp. 257-266, 1950 (summary in English).

WALDEN, HANS, HANS JAECKISCH, and FRITZ BRANDT, Zur Vorhersage von Hochdruckgebieten über Nordwesteuropa, An. Met., v. 3, no. 9-10, pp. 267-283, 1950 (summary in English).

WILLIAMS, PHILIP, JR., An objective method of forecasting summer precipitation at Salt Lake City, Utah, Mon. Wea. Rev., v. 78, pp. 148-152, 1950.

YAMAMOTO, T., On the secular change of the climate in Japan, pt. 2, Geophys. Mag., Tokyo, v. 22, no. 1, pp. 35-70, 1950.

BIBLIOGRAPHY: TERRESTRIAL MAGNETISM AND ELECTRICITY

ALFVÉN, H., Discussion of the origin of the terrestrial and solar magnetic fields, Tellus, v. 2, pp. 74-82, 1950 [abstr. in Phys. Abst., v. 53, no. 636, p. 971, 1950].

BARRE, M., and K. RAWER, Ionospheric observations in Adélie Land, C.-R. Acad. Sci., Paris, v. 231, pp. 436-437, Aug. 16, 1950 (in French) [abstr. in Phys. Abst., v. 53, no. 636, p. 1049, 1950].

BARTELS, J., 27-day variations in F_2 layer critical frequencies at Huancayo, J. Atmos. Terr. Phys., v. 1, no. 1, pp. 2-12, 1950 [abstr. in Phys. Abst., v. 53, no. 636, p. 1049, 1950].

BEAUFILS, Y., Rapid variations of telluric currents, C.-R. Acad. Sci., Paris, v. 230, pp. 2108-2110, 1950 (in French) [abstr. in Phys. Abst., v. 53, no. 634, p. 872, 1950].

BOCK, R., Die normale Verteilung der erdmagnetischen Vertikalintensität in Europa für die Epoche 1944.5, Gerlands Beiträge Geophysik, v. 61, pp. 104-115, 1949.

BOUŠKA, J., Experimental study of the geomagnetic gradients as a method of clarifying various geomagnetic problems, Čas. Pěst. Mat. Fis., v. 75, no. 2, pp. D155-D158, 1950 (in Czecho-slovakian) [abstr. in Chem. Abst., v. 53, no. 636, p. 1048, 1950].

BULLARD, E. C., C FREEDMAN, H. GELLMAN, and J. NIXON, The westward drift of the Earth's magnetic field, Phil. Trans. A, no. 859, 92 pp., 1950 [abstr. in Phys. Abst., v. 53, no. 636, p. 1048, 1950].

BURKARD, O., Ionosphärenbeobachtungen im Polargebiet, Archiv für Met., Geophys., Bioklim.; Ser. A, Met. Geophys., v. 1, no. 1, pp. 93-99, 1948 (summary in English).

BURKARD, OTTO, Studie über Höhenschwankungen der F2-Schicht; pt. 1, Geofis. Pura e Applicata, Milano, v. 15, pp. 3-8, 1949; pt. 2, v. 16, pp. 2-17, 1950 (summary in English).

BURKARD, O., Thermische Aufspaltung, ionosphärischer Schichten, Archiv. für Met., Geophys., Bioklim., Ser. A, Met. und Geophys., v. 2, no. 2-3, pp. 308-314, 1950 (summary in English).

BURKARD, O., Studie zur weltweiten Ionosphärenstörung vom 15. März 1948, Archiv für Met., Geophys., Bioklim., Ser. A, Met. Geophys., v. 2, no. 2-3, pp. 315-324, 1950 (summary in English).

BURKARD, OTTO, and RUDOLF EYFRIG, Studie über Höhenschwankungen der F2-Schicht; pt. 3, Geofis. Pura e Applicata, Milano, v. 16, pp. 8-12, 1950 (summary in English).

CARON, J , and R. VEILLITH, Relations entre l'activité solaire et quelques phénomènes terrestres, Urania, v. 35, no. 221-222, pp. 21-37, 1950.

CHAKRABARTY, S. K., "Sudden commencements" in geomagnetic field variations, Nature, v. 167, p. 31, 1951.

CORNISH, A., Navigation--from Ulysses to Cook, Naut. Mag., v. 164, pp. 28-32, 1950.

ERRULAT, F , Testing of the accuracy of a towed rotating apparatus by measurements of the vertical intensity of the Earth's magnetic field at sea along repeat profiles, Deutsche Hydrographische Zs., v. 3, pp. 249-257, 1950 (in German, with summary in English).

FALTINGS, V., and P. HARTECK, The tritium content of the atmosphere, Zs. Naturforsch., v. 5, pp. 438-439, Aug. 1950 (in German) [abstr. in Phys. Abst., v. 54, no. 637, p. 86, 1951].

FORSYTH, P. A., W. PETRIE, and B. W. CURRIE, On the origin of ten-centimeter radiation from the polar aurora, Can. J. Res., ser. A, v. 28, pp. 324-335, 1950 [abstr. in Phys. Abst., v. 53, no. 634, p. 877, 1950].

FUJITA, T., Micro-analytical study of thunder-nose, Geophys. Mag., Tokyo, v. 22, no. 2, pp. 71-88, 1950.

HAGGER, A. J., Air navigation in high latitudes, Polar Record, v. 5, pp. 440-449, 1950.

HARVEY, G. N., A new system of compass correction, J. Inst. Navig.,London, v. 1, pp. 197-218, 1948.

KAMIYAMA, HIROSHI, Seasonal variation of the minimum frequency in h'-f curve for the "E" ionospheric region, Sci. Rep., Tôhoku Univ., v. 2, no. 2, pp. 79-85, 1950.

KATO, YOSHIO, and TAKEHIKO KIKUCHI, On the phase difference of earth current induced by the changes of the Earth's magnetic field, pt. 1, Sci. Rep., Tôhoku Univ., v. 2, no. 2, pp. 139-141; pt. 2, pp. 142-145, 1950.

KATO, YOSHIO, SHINKICHI UTASHIRO, and JUSTO OSSAKA, On the changes of the terrestrial magnetic field accompanying the Tochigi earthquake of 26 Dec., 1949, Sci. Rep., Tôhoku Univ., v. 2, no. 2, pp. 149-152, 1950.

KRASOVSKII, V. I., New information about the radiation of the night sky in the region 8,800-11,000 A., Dokl. Akad. Nauk, SSSR, v. 70, no. 6, pp. 999-1000, 1950 (in Russian) [abstr. in Phys. Abst., v. 53, no. 634, p. 875, 1950].

MACLURE, K. C., Polar navigation, Arctic, v. 2, pp. 183-194, 1949.

MALAN, D. J., High-efficiency apparatus for lightning chronophotography, Rev. Opt. (Theor. Instrum.), v. 29, pp. 513-523, 1950 (in French) [abstr. in Phys. Abst., v. 54, no. 637, p. 86, 1951.

MARTYN, D. F., The theory of magnetic storms and auroras, Nature, v. 167, pp. 92-94, 1951.

MAY, W. E , The birth of the compass, J. Inst. Nav., London, v. 2, pp. 259-263, 1949.

NAGATA, T., The solar-flare type variation in geomagnetic field and the integrated electrical conductivity of the ionosphere, Rep. Ionosph. Res. in Japan, v. 4, pp. 155-172 and 201-205, 1950.

NAGATA, TAKESI, and TAKESHI WATANABE, Magnetic properties of the rocks containing maghemite, (γ - Fe_2O_3), Geophys. Notes, Geophys. Inst., Tokyo Univ., v. 3, no. 21, 8 pp., 1950.

NEHER, H. V., Correlation of geomagnetic cosmic-ray effects, Phys. Rev., v. 78, pp. 674-680, 1950 [abstr. in Phys. Abst., v. 53, no. 634, p. 839, 1950].

NORINDER, H., and O. SALKA, The effect of geological discontinuities on artificial lightning discharges as studied in a model test arrangement, Ark. Geofys., v. 1, paper 3, pp. 45-78, 1950 [abstr. in Phys. Abst., v. 53, no. 634, p. 876, 1950].

ORIOL CARDÚS, J., Sobre la ley de las fases en las corrientes telúricas, Rev. Geofis., v. 9, no. 35, pp. 215-233, 1950 (summary in English).

PETRIE, W., The near-infrared spectrum of the polar aurora, J. Geophys. Res., v. 55, pp. 143-152, 1950 [abstr. in Phys. Abst., v. 53, no. 635, p. 962, 1950].

PINEO, V. C , A comparison of meteor activity with occurrence of sporadic E reflections, Science, v. 112, no. 2898, pp. 50-51, 1950.

RODIONOV, S. F., and L. M. FISHKOVA, On the infrared radiation of northern lights, Dokl. Akad. Nauk, SSSR, v. 70, no. 6, pp. 1001-1003, 1950 (in Russian) [abstr. in Phys. Abst., v. 53, no. 634, p. 877, 1950].

RUNCORN, S. K., The main geomagnetic field, Sci. Prog., v. 38, pp. 668-677, 1950 [abstr. in Phys. Abst., v. 54, no. 637, p. 85, 1951].

RUNCORN, S. K , A. C. BENSON, A. F. MOORE, and D. H. GRIFFITHS, The experimental determination of the geomagnetic radial variation, Phil. Mag., v. 41, pp. 783-791, 1950.

SCHUMANN, WOLFGANG, Über die Einführung und Bedeutung einer Eisen-Charakterzahl für Minerale, Gerlands Beiträge Geophysik, v. 61, pp. 70-78, 1949.

SEKIDO, Y., M. KODAMA, and T. YAGI, Time variation of vertical cosmic rays, Rep. Ionosph. Res. in Japan, v. 4, pp. 207-213, 1950.

STEFANESCU, SABBA S., Das elektromagnetische Normalfeld des waagerechten Niederfrequenzdipols, pt. 2, Gerlands Beiträge Geophysik, v. 61, pp. 195-219, 1950.

TAYLOR, E. G. R., The early navigator, Geog. J., v. 113, pp. 58-61, 1949.

THEISSEN, E., Thickness data for the F_2 layer of the ionosphere for the parabolic model, Naturwissenschaften, v. 37, no. 14, pp. 334-335, 1950 (in German) [abstr. in Phys. Abst., v. 53, no. 636, p. 1049, 1950].

BIBLIOGRAPHY: OCEANOGRAPHY

BERTHOIS, L., Sur la corrélation entre l'importance du volume des déplacements de l'air et l'évolution littorale, C.-R., v. 230, pp. 2110-2111, 1950.

BULLIG, H. J., Ueber Wassertemperaturanomalien des östlichen Atlantischen Ozeans und ihre meteorologische Bedingtheit, Ber. Deutsch. Wetterdienst, U. S. Zone, no. 12, pp. 137-140, 1950.

CARRUTHERS, J. N., H. G. STUBBINGS, and A. L. LAWFORD, Water sampling in estuarial waters, Dock. Harb. Auth., v. 31, pp. 253-259, 1950.

COLLIER, ALBERT, and J. W. HEDGPETH, An introduction to the hydrography of tidal waters of Texas, Publ. Inst. Mar. Sci., v. 1, no. 2, pp. 125-194 + 6 pl., 1950.

DARBYSHIRE, J., Identification of microseismic activity with sea waves, Proc. R. Soc., A, v. 202, pp. 439-448, 1950.

DARMOIS, R , and J. DARMOIS, Observations de température et salinité préparatoires à l'étude de la viscosité de l'eau de la Méditerranée au large de Monaco, C.-R., v. 225, pp. 1081-1082, 1947.

DIETRICH, GÜNTER, Die natürlichen Regionen von Nord- und Ostsee auf hydrographischer Grundlage, Kieler Meeresforschungen, v. 7, no. 2, pp. 35-69, 1950.

DOBRIN, MILTON B., Submarine geology of Bikini Lagoon as indicated by dispersion of waterborne explosion waves, Bull. Geol. Soc. Amer., v. 61, pp. 1091-1118, 1950.

EMERY, K. O., and R. E. STEVENSON, Laminated beach sand, J. Sed. Petr., v. 20, pp. 220-223, 1950.

FRIEDMAN, BERNARD, Theory of underwater explosion bubbles, Comm. Pure Appl. Math., v. 3, pp. 177-199, 1950.

HAHN, JAN, Some aspects of deep sea underwater photography, J. Phot. Soc. Amer., Ser. B, pp. 27-29, June 1950.

HORRER, P. L., Wave forces computed for a typical offshore drilling site, J. Petr. Technol., v. 1, pp. 299-304, 1949.

IRIBARREN CAVANILLES, R., and C. NOGALES Y OLANO, Planos de oleaje en segunda approximación, Rev. Obras Púb., v. 97, pp. 519-534, 593-601, 1949.

ISELIN, COLUMBUS O'D., Some common characteristics of the Gulf Stream and the atmospheric jet stream, Trans. N. Y. Acad. Sci., ser. 2, v. 13, pp. 84-86, 1950.

KETCHUM, B. H., Hydrographic factors involved in the dispersal of pollutants introduced into tidal waters, J. Boston Soc. Civ. Eng., v. 37, pp. 296-314, 1950.

LAWSON, ANDREW C., Sea bottom off the coast of California, Bull. Geol. Soc. Amer., v. 61, pp. 1225-1242, 1950.

LEIPPER, D. F., and E. R. ANDERSON, Sea temperatures, Hawaiian Island area, Pac. Sci., v. 4, pp. 228-248, 1950.

LONGUET-HIGGINS, M. S., A theory of the origin of microseisms, Phil. Trans., A, v. 243, pp. 1-35, 1950.

MENARD, H. W , and A. J. BOUCOT, Experiments on the movement of shells by water, Amer. J. Sci., v. 249, pp. 131-151, 1951.

MUNK, W. H., and G. F. CARRIER, The wind-driven circulation in ocean basins of various shapes, Tellus, v. 2, pp. 158-167, 1950.

NASU, N., Local phenomena of tsunami, pt. 2, Bull. Earthquake Res. Inst., Tokyo Univ., v. 26, pp. 27-35, 1948.

OGIWARA, S., and T. OKITA, Studies in tsunami on the Pacific coasts of northern Honshu, pt. 1, The model experiment of tsunami in Shizukawa harbour, Sci. Rep. Tôhoku Univ., ser. 5, v. 2, pp. 58-65, 1950.
REDFIELD, ALFRED C., Some applications of oceanography to engineering problems, J. Boston Soc. Civ. Eng., v. 37, pp. 275-295, 1950.
ROUCH, J., La densité de l'eau de mer et les courants au voisinage de Monaco, Bull. Inst. Océan., no. 968, 12 pp., 1950.
ROUX, G., La prévision de la houle sur la côte atlantique du Maroc, Bull. Sci. Comité Oceanogr. et Côtes Maroc, no. 5, pp. 3-8, 1949.
SPITZER, LYMAN (Chairman, Panel on Underwater Acoustics), Underwater acoustics research, Committee on Undersea Warfare, Nat. Res. Council, 137 pp., Washington, D. C., 1950.
THOM, A. S., Investigation of tidal phenomena in the Clyde estuary, using a scale model, J. Inst. Civ. Eng., v. 33, pp. 100-125, 1949.
VAN BAREN, F. A., and H. KIEL, Contribution to the sedimentary petrology of the Sunda Shelf, J. Sed. Petr., v. 20, pp. 185-213, 1950.
WEBSTER, JOHN R., and R. J. BILLER, Drift bottle releases off New Jersey; a preliminary report on experiments begun in 1948, Fish and Wildlife Serv. Spec. Sci. Rep., Fisheries no. 10, 21 pp., Washington, D. C., 1950.
WEITZ, MORTIMER, and J. B. KELLER, Reflection of water waves from floating ice in water of finite depth, Comm. Pure Appl. Math., v. 3, pp. 305-318, 1950.

BIBLIOGRAPHY: VOLCANOLOGY

ALEVA, GERARDUS J. J., Geology and petrology of the Gabbi-Mesket region, Swedish Lapland, dissertation, Geol. Inst., Univ. Amsterdam, pp. 1-158, 1950.
BATTEY, M. H., The geology of Rangiawhia Peninsula, Doubtless Bay, North Auckland, Records, Auckland Inst. Museum, New Zealand, v. 4, no. 1, pp. 35-59, 1950.
BOARETTO, ROSA M., Azioni metamorfiche di contatto nei calcari marnosi anisci dell'Alta Val Cadino (Adamello meridionale), Periódico di Mineralogia, v. 19, no. 2-3, pp. 183-206, 1950.
BOUMAN, Q. C., The dolerite intrusions of the Wellington-Morreesburg area, An. Univ. Stellenbosch, v. 26, sec. A, no. 3-11, pp. 287-305, 1950.
BRAK-LAMY, J. A. N., and A. de V. T. P. COELHO, Rochas do distrito de Tete, Mozambique, Ministerio das Colonias, Rep. Portugesa, Mem., Ser.-Geol. no. 2, pp. 1-29, 1945.
BRINK, W. C., The geology, structure, and petrology of the Nuwerus area, Cape Province, An. Univ. Stellenbosch, v. 26, sec. A, no. 3-11, pp. 97-221, 1950.
CAMPBELL, CHARLES D., Petrology of the Columbia River basalts: Present status and ideas for future work, Northwest Sci., v. 24, no. 2, pp. 74-83, 1950.
CONTI, SERGIO, Un grande massiccio frammentario gneissico-granitico nelle Alpi Liguri, Atti della Acad. Nazionale dei Lincei, Rome, mem. ser. 8, v. 2, fasc. 3, Classe Sci., fis., math., e naturali, pp. 45-69, 1950.
de ANDRADE, M. M., Nova granito hiperalcalino de Angola, Memórias e Noticias Museu e Lab. Miner. e geol. e do centro de estudos geol., Univ. de Coimbra, no. 28, pp. 9-19, 1950.
de ANDRADE, M. M., Novas rochas basalticas do Litoral de Angola, Memórias e Noticias Museu e Lab. Miner. e geol. e do Centro de Estudos Geol., Univ. de Coimbra, no. 28, pp. 20-25, 1950.
de ANDRADE, M. M., Estado actual dos conhecimentos sobre as rochas ígneas de Angola, Memórias e Noticias Museu e Lab. Miner. e geol. e do Centro de Estudos Geol., Univ. de Coimbra, no. 27, pp. 35-99, 1950.
EGEBER, C. G., On metamorphic rocks from the island of Kabaena in the East-Indian Archipelago, Koninklijke Nederlansche Akad. Wetenschappen, Proc., v. 52, no. 5, pp. 551-562, 1949.
EYLES, V. A., Note on the interbasaltic horizon in Northern Ireland, Q. J. Geol. Soc., London, v. 106, pt. 1, no. 421, pp. 136-137, 1950.
FRIEDMAN, IRVING, Immiscibility in the system H_2O-Na_2O-SiO_2, J. Amer. Chem. Soc., v. 72, pp. 4570-4574, 1950.
FRIEDMAN, IRVING, Some aspects of the system H_2O-Na_2O-SiO_2-Al_2O_3, J. Geol., v. 59, no. 1, pp. 19-31, 1951.
GONZALEZ BONORINO, FELIX, Geologia y petrografia des las Hojas 12d (Capillitas) y 13d (Andalgala), Ministerio de Industria y Comercio de la Nación, Argentina, Bol. no. 70, pp. 1-99, 1950.
GORAI, MASAO, The features of plagioclase twinning in various granitic rocks, J. Geol. Soc. Japan, v. 56, no. 663, pp. 515-518, 1950.
HEM, JOHN D., Geochemistry of ground water, Econ. Geol., v. 45, pp. 72-81, 1950 [abstr. in Chem. Abst., v. 45, no. 2, p. 791, 1951].
HOFFET, J. H , Notes sur la géologie de la Province du Haut-Mékong, Bull. du Service Géol. Indochine, v. 29, fasc. 2, 21 pp., 1950.

HUBER, WALTER, Geologisch-petrographe Untersuchungen in der Innern Fjordregion des Kejser Franz Josephs Fjordsystems in Nordostgrönland, Med. om Grønland, v. 151, no. 3, 83 pp., 1950.

ICHIMURA, TAKESHI, A brief geological note on the Kuanyin Volcano, Formosa, J. Geol. Soc. Japan, v. 56, no. 662, pp. 493-498, 1950.

ICHIMURA, T., R. MORIMOTO, and H. TSUYA, A brief note on the recent explosive activity of Volcano Yakeyama, Bull. Earthquake Res. Inst., Tokyo Univ., v. 27, pp. 107-114 + 6 fig., 1949.

ISHIMORI, TOMITARO, Chromium content of volcanic rocks, Bull. Chem. Soc. Japan, v. 23, no. 3, pp. 75-76, 1950.

JÉREMINE, E., Étude petrographique des roches éruptives et métamorphiques du massif de Bou Agrao, Notes Service Geol., v. 2, no. 74, pp. 119-147, 1950.

JUGOVICS, LAJOS, Beiträge zur Kenntnis der Gesteine von Ost-Celebes, Geologica Hungarica, Geologica, v. 8, pp. 1-112, 1950.

KING, L. C., Geology of Pietermaritzburg and environs, Univ. South Africa, Dept. Mines, Geol. Surv., Spec. Pub., 21 pp., 1948.

KORZHINSKII, D. S., Thermodynamic potentials of open systems and their application in geochemistry, Izvest. Sektora Fiz.-Khim. Anal. Inst. Obschchel i Neorg. Khim., Akad. Nauk SSSR, v. 19, pp. 41-50, 1949 (in Russian) [abstr. in Chem. Abst., v. 44, no. 20, p. 9308, 1950].

KUNO, HISASHI, Composite lava flows and dikes found in North Izu, Japan, J. Geol. Soc., Japan, v. 56, pp. 167-172, 1950 [abstr. in Chem. Abst., v. 45, no. 1, p. 81, 1951].

KUNO, HISASHI, Some problems on the volcanoes and volcanic rocks of Japan, J. Geol. Soc., Japan, v. 56, pp. 226-231, 1950 [abstr. in Chem. Abst., v. 45, no. 1, p. 81, 1951].

LEINZ, VIKTOR, Pequenas notas geológicas e petrográficas sôbre o território do Amapá, Bol. Museu Nacional, n. s. Geologica, no. 7, pp. 1-16, 1949.

LUNDEGARDH, P. H., Aspects to the geochemistry and petrology of plutonic ultrabasites in Sweden, Geol. Fören. Stockholm Förh., v. 72, pp. 51-63, 1950 [abstr. in Chem. Abst., v. 44, no. 22, p. 9620, 1950].

MORIMOTO, R., A petrological note on the granitic rocks near the Cape Ashizuri, Shikoku Island, Japan, pt. 2, Bull. Earthquake Res. Inst., Tokyo Univ., v. 27, pp. 45-48, 1949.

NEIVA, J. M. COTELO, and T. LOPEZ de CASTRO, Granite and the Senhora da Hora kaolin deposit (Porto), Memórias e Noticias Museu e Lab. Miner. e Geol. e do Centro de Estudos Geol., Univ. de Coimbra, no. 28, pp. 49-66, 1950.

NIINI, RISTO, The rate of cooling of the initial crust of the Earth, Geologi, v. 2, pp. 29-30, 1950 [abstr. in Chem. Abst., v. 44, no. 21, p. 9878, 1950].

ORSENIGO, G. FAGNANI-L., Il granofiro di Boarezzo e le manifestazioni metallifere che lo accompagnano, Atti della Soc. Italiana di Scienze Naturali e del Museo Civico, v. 59, pp. 21-32, 1950.

PATTERSON, EDWARD M., A preliminary note on the tertiary lava succession in North Antrim, Q. J. Geol. Soc. London, v. 106, pt. 1, no. 421, pp. 134-135, 1950.

PEREIRA, J. D. S., Algunas notas relativas à petrografia da India Portuguesa, Junta das missões Geograficas e de Investigações Coloniais, Mem. ser. de Geol. Econ., v. 1, no. 2, 32 pp., 1949.

POTGIETER, C. T., The structure and petrology of the George Granite Plutons and the invaded Pre-Cape sedimentary rocks, An. Univ. Stellenbosch, v. 26, sec. A., no. 3-11, pp. 323-412, 1950.

RAO, G. PRABHAKARA, The geology of the manganese bearing rocks of Garividi and Garbham, Vizagapatam District, Q. J. Geol., Min. Metal. Soc. India, v. 22, no. 2, pp. 25-42, 1950.

RAUGIN, E., Observations sur le massif de syenite du Bou Agrao pres de Midelt, Notes Service Geol., no. 74, v. 2, pp. 149-155, 1950.

RIKITAKE, T., A note on the temperature distribution within the Earth, Bull. Earthquake Res. Inst., Tokyo Univ., v. 27, pp. 17-20, 1949.

RUTTEN, L., and W. HOTZ, Geological, petrographical, and palaentological results of explorations carried out from September 1917 till June 1919 in the Island of Ceram, Third Ser. Geol., no. 3 of J. P. van der Sluis Geology of East Seran, Amsterdam, 1950.

SAKUMA, S., and T. MINAKAMI, Minor activity of Volcano Yake-yama in 1949, Bull. Earthquake Res. Inst., Tokyo Univ., v. 27, pp. 117-121 + 9 fig., 1949.

SEARLE, E. J., A vitreous sedimentary bomb from the pyroclastic material at Auckland, New Zealand, Trans. Proc. R. Soc., New Zealand, v. 78, pt. 4, pp. 479-481, 1950.

SHIBATA, HIDEKATA, Mineralizations in the granite pegmatites in Japan and Korea, pt. 1, Sci. Rep., Tokyo Bunrika Daigaku, Section C, v. 6, no. 8, pp. 1-27, 1949.

TILLEY, C. E., Some aspects of magmatic evolution, Q. J. Geol. Soc. London, v. 106, pt. 1, no. 421, pp. 37-61, 1950.

TSUYA, H., T. ICHIMURA, and T. SHIRAI, Hydrated aluminum-sulphate minerals from new fumaroles on Volcano Yakeyama, Niigata Prefecture, Bull. Earthquake Res. Inst., Tokyo Univ., v. 27, pp. 115-116 + 4 fig., 1949.

TSUYA, H., and T. SHIRAI, Gases and deposits from fumaroles on the New Dome "Showa-Shinzan," Volcano Usu, Hokkaido, Japan, Bull. Earthquake Res. Inst., Tokyo Univ., v. 27, pp. 135-139 + 3 fig., 1949.

van ZYL, P. J., The complex dioritic stocks west of the Malmesbury Paardeberg Granite Pluton, An. Univ. Stellenbosch, v. 26, sec. A, no. 3-11, pp. 481-507, 1950.

WAHLSTROM, ERNEST E., Theoretical igneous petrology, John Wiley, 365 pp., 1950.

WELLMAN, H. W., Metamorphic gradient, Kent coalfield, England, Econ. Geol., v. 43, pp. 499-508, 1948 [abstr. in Chem. Abst., v. 44, no. 22, p. 10619, 1950].

BIBLIOGRAPHY: HYDROLOGY

ALVIR, A. D., Candaba Swamp; its origin and its relation to flood control, Philippine Geologist, v. 4, no. 4, pp. 6-10, Sep. 1950.

BAULIG, H., Les inondations de Décembre 1947, An. Inst. Physique du Globe, n.s., v. 5, pt. 3, Geophys., pp. 39-48, 1950.

BERGSTEN, FOLKE, Contribution to study of evaporation in Sweden, Swedish Met. Hydrol. Inst., Comm. Ser. D, no. 3, 57 pp., 1950.

BLOCKS, SHIRLEY J., Rainfall, runoff, and power with special reference to Ceylon, Central Bd. of Irrig. J., v. 7, pp. 194-198, Mar. 1950.

BOGARDI, J., Suspended silt transportation by the Tisza River on the Záhony-Rázompuszta section, Hungarian Water Board, no. 3-4, pp. 143-188, 1949 (in Hungarian with summary in English).

BOURGUIGNON, P., Présentation de deux manomètres de précision pour le contrôle piézométrique des débits et la mesure de variations rapides de pression, La Houille Blanche, v. 2, no. 2, pp. 165-174, 1950 (summary in English, p. 112).

CARRY, CL., Average velocity of materials in suspension, Int. Assn. for hyd. Str. Res., v. 2, no. 8, 15 pp., Sep., 1949 (in French) [abstr. in Appl. Mech. Rev., v. 3, no. 12, p. 410, 1950].

CHHIBBER, H. L., The development of land forms, soils, and life in the neighbourhood of Jubbulpore and Bheraghat, Madhya Proidesh, Nat. Geol. Soc. India, Banares, Bull. 14, 64 pp., April, 1950.

CLYDE, GEORGE D., Utilization of natural underground water storage reservoirs, J. Soil Water Cons., v. 6, no. 1, pp. 15-19, Jan., 1951.

COLAS, R., Radioactivité et pollution de l'eau, L'Eau, v. 37, no. 11, pp. 157-163, Nov., 1950.

COLLENS, B. W., Ground water in North Canterbury between the Waimakariri and Ashley Rivers, New Zealand J. Sci. Tech., v. 30, no. 5, sec. B, pp. 249-268, March, 1949.

COUTAGNE, ..., Que sait-on des débits de la Seine à Paris, Mém. Trav. Soc. Hydrotech., La Houille Blanche, v. 2, no. 2, p. 118, 1950.

CRAYA, A., Schemes of suspension in variable regime, Int. Assn. for Hyd. Str. Res. II-7, 19 pp., Sep., 1949 (in French) [abstr. in Appl. Mech. Rev., v. 3, no. 12, p. 410, 1950].

DAVIS, LEON V., Ground water in the Pond Creek Basin, Caddo County, Oklahoma, Okla. Geol. Surv. Min. Rep. 22, 23 pp., 1950.

DENNIS, P. E., Ground water in the Wimbledon area, Barnes and Stutsman counties, North Dakota, N. Dak. Ground-Water Studies 10, pp. 1-38, 1948 [abstr. in Chem. Abst., v. 45, no. 3, p. 1275, 1951].

DENNIS, P. E., and P. D. AKIN, Ground water in the Portland area, Traill County, North Dakota, N. Dak. Ground-Water Studies 15, pp. 1-50, 1950 [abstr. in Chem. Abst., v. 45, no. 2, p. 791, 1951].

DENNIS, P. E., P. D. AKIN, and SUZANNE L. JONES, Ground water in the Kindred area, Cass and Richland counties, North Dakota, N. Dak. Ground-Water Studies 14, pp. 1-75, 1950 [abstr. in Chem. Abst., v. 45, no. 2, p. 791, 1951].

DEVROEY, E. J., Les sources du Nil au Congo Belge et au Ruanda-Urundi, Bull. Séances, Inst. R. Col. Belge, v. 21, no. 1, pp. 248-279 + 7 fig., 1950.

DOEGLAS, D. J., De Interpretatie van Karrelgrootte-Analysen, Verhandelengen van Het Nederlandsch Geologisch-Mijnbouwkundig Genootschop, pp. 227-328, July, 1950.

DUBIEF, J., Evaporation et coefficients climatiques au Sahara, Trav. Inst. Recherches Sahariennes, v. 6, pp. 13-44, 1950.

EAST, W. GORDON, The Severn waterway in the eighteenth and nineteenth centuries, London Essays in Geogr., London Sch. of Econ. and Political Sci., Univ. of London, Harvard Univ. Press, pp. 91-110, 1951.

EINSTEIN, HANS ALBERT, The bed-load function for sediment transportation in open channel flows, U. S. Dept. Agri. Tech. Bull. 1026, 71 pp., Sept., 1950.

ESCANDE, ..., Calcul des oscillations de l'eau dans des bassins communicants, Mém. Trav. Soc. Hydrotech., La Houille Blanche, v. 2, no. 2, p. 117, 1950.

FOOSE, RICHARD M., Studies of the relationship between the chemistry of ground water, movement of ground water, and rock types, Proc. Pennsylvania Acad. Sci., v. 24, pp. 151-154, 1950.

FOOSE, RICHARD M., Ground-water conservation and development, Pennsylvania Dept. Internal Affairs, v. 19, no. 2, pp. 17-28, Jan., 1951.

FRANK, BERNARD, and ANTHONY NETBOY, Water, land, and people, Alfred A. Knopf, 331 pp., 1950.

FRASELLE, E , Le problème des cycles hydrographiques et climatologiques du Bassin de la Kagera (Vicotria-Nyanza), Bull. Séances, Inst. R. Col. Belge, v. 21, no. 1, pp. 235-247, 1950.

GARCIA QUINTERO, ANDRÉS, Hydrology of Mexico, Proc. Amer. Soc. Civil Eng., v. 76, 17 pp., Oct., 1950.

GOHARA, Y., On the prospecting method for the ground water, Misc. Rep. Tokyo Res. Inst. Natural Resources no. 16, pp. 33-42, Mar., 1950 (in Japanese with summary in English).

GOTTSCHALK, L. C., Measurement of sedimentation in small reservoirs, Proc. Amer. Soc. Civil Eng., v. 77, 11 pp., Jan., 1951.

GRAHAM, JACK B., Pennsylvania water resources and water uses, Proc. Pennsylvania Acad. Sci., v. 24, pp. 220-229, 1950.

GRIDEL, H., La mesure précise et l'enregistrement des niveaux stables ou fluctuants au moyen de pointes limnimetriques à vibrations entretenues, La Houille Blanche, v. 2, no. 2, pp. 185-191, 1950 (summary in English, p. 113).

HAMILTON, DAN K., Areas and principles of ground-water occurrence in the inner Bluegrass Region, Kentucky, Ky. Geol. Surv. Bull. 5, 67 pp. + 15 maps, 1950.

HEM, JOHN D., Quality of water of the Gila River Basin above Coolidge Dam, Arizona, U. S. Geol. Surv. Water-Supply Paper 1104, 230 pp., 1950.

HEMBREE, CHARLES H., KENNETH R. MELIN, MARION C. BOYER, and HERBERT A. SWENSON, Progress report, sedimentation and chemical quality of water in the Bighorn River Drainage Basin, Wyoming and Montana, U. S. Geol. Surv., Water Res. Div., 163 pp. + 20 tables, July, 1950.

HEWITT, F. A., R. C. BAKER, and G. A. BILLINGSLEY, Ground-water resources of Ashley County, Arkansas, Univ. Ark. Bull. 42, no. 14, Research Ser. no. 16, pp. 1-35, 1949 [abstr. in Chem. Abst., v. 45, no. 2, p. 791, 1951].

HILLEBRAND, DIETRICH, Verkrautung und Abfluss, Besondere Mitteilungen, Deutschen Gewässerkundlichen Jb., Hannover, 18 pp. + 9 fig., 1950.

INGLIS, C., The effect of variations of charge and grade on the slopes and shapes of channels, Inst. Assn. for Hyd. Str. Res. II-1, 10 pp., Sep., 1949 [abstr. in Appl. Mech. Rev., v. 3, no. 12, p. 410, 1950].

IRMAY, S , On steady flow formulae in pipes and channels, Int. Assn. for Hyd. Str. Res. III-3, 11 pp., 1949 [abstr. in Appl. Mech. Rev., v. 3, no. 12, p. 410, 1950].

JAMISON, V. C., H. A. WEAVER, and L. F. REED, A hammer-driven soil-core sampler, Soil Sci., v. 69, pp. 487-496, 1950 [abstr. in Chem. Abst., v. 44, no. 22, p. 10979].

JEFFORDS, RUSSELL M., The ground-water resources of Montgomery County, New York, N. Y. Dept. Conservation, Water Power and Control Comm., Bull. GW-23, pp. 1-63, 1950 [abstr. in Chem. Abst., v. 45, no. 1, p. 289, 1951].

KING, LESTER C., The study of the world's plainlands: A new approach in geomorphology, Q. J. Geol. Soc. London, no. 421, v. 106, pt., pp. 101-131, Dec., 1950.

KLAER, FRED H., JR., Ground-water levels in Indiana, Proc. Ind. Acad. Sci., v. 59, pp. 236-245, 1950.

KOCH, P., La violence des orages dans ses relations avec le débit des égouts urbains, La Houille Blanche, v. 2, no. 2, pp. 155-158, 1950 (summary in English, p. 112).

LA MOREAUX, P. E., G. W. SWINDEL, JR., and C. R. LAINPHERE, Ground-water resources of the Huntsville area, Alabama, Geol. Sorv. Ala., Bull. 62, 82 pp., 1950.

LATTA, BRUCE F., Geology and ground-water resources of Barton and Stafford Counties, Kansas, Kans. Geol. Surv. Bull. 88, 228 pp., 1950.

LITTLETON, ROBERT T., Reconnaissance of the ground-water resources of the Wheatland Flats area, Wyoming, U. S. Geol. Surv. Circ. 70, 32 pp., 1950 (processed).

LITTLETON, ROBERT T., and HERBERT A. SWENSON, Geology and ground-water hydrology of the Angostura irrigation project, South Dakota, U. S. Geol. Surv. Circ. 54, pp. 1-96, 1949 [abstr. in Chem. Abst., v. 45, no. 3, p. 1275, 1951].

LOMBARDI, J., and G. MARQUENET, Méthode de calcul d'un chenal en escalier et à biefs affouillables pour la régularisation d'un torrent, La Houille Blanche, Spec. B, pp. 730-746, Nov., 1950.

MARCHI, GIULIO, Caratteristiche idrologiche e idrauliche dei grandi laghi subalpini, Direzione Generale del Catasto e dei Servizi Tecnici Erariali, Roma, no. 84, 1950.

MEAD, DANIEL W., Hydrology, second ed., revised and enlarged, McGraw-Hill, 728 pp., 1950.

MORLAT, ..., Sur la consigne d'exploitation optimum des réservoirs saisonniers, La Houille Blanche, v. 2, no. 2, p. 130, 1950.

NADEAU, REMI A., The water seekers, Doubleday Country Life Press, Garden City, N. Y., 309 pp., 1950.

NIZERY, ANDRÉ, Note sur l'entrainement des matériaux par charriage, La Houille Blanche, Spec. A, 8 pp., 1949.
NORRIS, STANLEY E., WILLIAM P. CROSS, and RICHARD P. GOLDTHWAIT, The water resources of Greene County, Ohio, Ohio Dept. Nat. Res., Div. of Water, Bull. 19, Jan., 1951.
PARDÉ, M., Sur le mécanisme des transports solides effectués par les rivières et sur les altérations corrélatives des lits fluviaux, Rev. Géogr. Alpine, v. 39, pp. 5-40, 1951.
PENMAN, H. L., The water balance of the Stour catchment area, J. Inst. Water Eng., v. 4, no. 6, pp. 457-469, Oct., 1950.
REMENIERAS, G., Application de l'électroosmose à l'exécution de certains travaux en terrains aquifères, La Houille Blanche, Spec. A, 12 pp., 1949.
SCEVA, JACK E., Preliminary report on the ground-water resources of southwestern Skaget County, Washington, Washington (State) Ground-Water Rep. 1, 40 pp. + 2 pl., Dec., 1950.
SERPAUD, J , The measurement of suspended matter in water, Hidrol. Közlöny, v. 29, pp. 42-44, 1949 [abstr. in Chem. Abst., v. 45, no. 3, p. 1278, 1951].
SILBER, R., Étude des écoulements permanents graduellement variés en canaux découverts, La Houille Blanche, v. 2, no. 2, pp. 138-149, 1950 (summary in English, p. 111).
SILBER, R., Écoulements au voisinage de la profondeur critique, La Houille Blanche, v. 2, no. 2, p. 128, 1950.
SULZLÉE, C., Rapport sur la mission d'étude effectuée auprès de l'Institut pour l'étude de la neige et des avalanches de Weissfluhjoch-s/Davos, La Houille Blanche, v. 2, no. 2, pp. 175-184, 1950 (summary in English, p. 113).
SUNDSTROM, R. W., and C. R. FOLLETT, Ground-water resources of Atascosa County, Texas, U. S. Geol. Surv., Water-Supply Paper 1079-C, pp. 107-152, 1950.
TAYLOR, GEORGE C., JR., Geology and ground water of the Azapa Valley, Province of Tarapacá, Chile, Econ. Geol., v. 44, pp. 40-62, 1949 [abstr. in Chem. Abst., v. 45, no. 2, p. 791, 1951].
TSUJI, M., On the rate of evaporation and condensation of falling drops, Geophys. Mag., Tokyo, v. 22, pp. 11-14, Oct., 1950.
UPPAL, H. L., A study of certain aspects of transportation of bed load in line canals, Int. Assn. for Hyd. Str. Res. II-4, 25 pp., 1949 [abstr. in Appl. Mech. Rev., v. 3, no. 12, p. 410, 1950].
VAN EIMERN, JOSEF, Meteorologisch bedingte Kleinschwankungen des Grundwasserstandes, An. Met., Hamburg, v. 3, no. 7-8, pp. 215-223, 1950 (summary in English).
VAN TUYL, D. W., Ground-water resources of the valley-fill deposits in the Pittsburgh area, Proc. Pennsylvania Acad. Sci., v. 24, pp. 155-160, 1950.
WARREN, H. N. (Director), Results of rainfall observations made in New South Wales, Sections I-VI, Districts 46-75, including rainfall tables (monthly and annual), discussion of rainfall and its relation to primary industries, and also temperature and humidity tables, records of floods, cyclones, and local storms, Bur. Met., Australia, 546 pp. + 36 appendices + 38 maps, 1948.
WAYNE, WILLIAM J., A karst valley in western Monroe County, Indiana, Proc. Ind. Acad. Sci., v. 59, pp. 258-263, 1950.
WILLIAMS, TREVOR I., Control of flowing water, Sci. and Eng., v. 111, pp. 197-198, Oct., 1950.
WYART, PIERRE, Monographie hydrologique du Guil, La Houille Blanche, Spec. A, 19 pp., 1950.
YOST, IVAN D., Flood of August 1-6, 1950, at Wichita Falls, Texas, U. S. Geol. Surv. Circ. 99, 18 pp., Jan., 1951.
YUSUPOV, B. M., Subterranean waters in the Lower Kama Region, Geol. Inst. Kazen. Filiala, Akad. Nauk SSSR, Dokl. Akad. Nauk SSSR, v. 60, pp. 1389-1392, 1948 [abstr. in Chem. Abst., v. 45, no. 1, p. 289, 1951].

BIBLIOGRAPHY: TECTONOPHYSICS

ALASTRUÉ, EDUARDO, Las Unidades estructurales de las Cordilleras béticas según los estudios del Dr. Blumenthal, Inst. Geol. Min. España, Bull. 62, pp. 1-67, 1949.
BROUWER, H. A., Sur la tectonique de la Corse, Konink. Nederlandse Akad. Wetensch., Proc., v. 53, no. 1, pp. 3-8, 1950.
CAMERON, H. L., Faulting in the vicinity of Halifax, Nova Scotia, Proc. Nova Scotia Inst. Sci., v. 22, pt. 3, pp. 1-15, 1950.
KETIN, I., Über die tektonishen Ergebnisse der Geländeaufnahme des Gebiets Ergani - Eğil im Südost-Antolien, Revue Faculté Sci. Univ. Istanbul, Ser. B, v. 15, no. 2, pp. 153-160, 1950.
MORET, LÉON, Les idées nouvelles sur l'origine des chaines de montagnes, Rev. géogr. Alpine, v. 38, no. 2, pp. 223-278, 1950.
RÜEGG, W., and D. FYFE, Some outlines on the tectonics of the upper Amazon embayment, Intern. Acad. Congr. "Report of the Eighteenth Session, Great Britain, 1948," pt. 6, pp. 77-85, 1948.
SEIICHI, HIGUCHI, and MASAHIKO SUZUKI, Distribution of stresses in the semi-infinite plate having elliptic notch under uniform tension, Tôhoku Univ., tech. reports, v. 14, no. 1, pp. 95-107, 1949.

TURNER, J. S., The deeper structure of central and northern England, Proc. Yorkshire Geol. Soc., v. 27, pt. 4, pp. 280-297, 1949.
VERSEY, H. C., The structure of East Yorkshire and North Lincolnshire, Proc. Yorkshire Geol. Soc., v. 27, pt. 3, pp. 173-191, 1948.

NOTES AND PERSONALIA

NOTES

Corrigenda--In the December 1950 issue, the last line on page 871 (Chayes' paper) should read ". . . . corresponding to intercept lengths of 0.05 to 1.25 mm." The 0.5 in the published paper is in error.

In the February 1951 issue, page 61 (Schiff's paper), column 10, headed v_a, the seventh item down should be 0.09, not 4073.

The joint expedition of the Scripps Institution of Oceanography and the U. S. Navy Electronics Laboratory to the Mid-Pacific--The motor vessel Horizon of the Scripps Institution (a converted Navy fleet tug, formerly ATA-180) and the EPCE(R)-857 (a 220-foot research vessel assigned to the U. S. Navy Electronics Laboratory) returned from a three-months' expedition to the eastern central Pacific, between San Diego, the equator, and the Marshall Islands, and extending north as far as 40° north latitude. The ships traveled a total of 29,000 miles.

Some 30 scientists participated in the expedition representing five scientific institutions: the Scripps Institution of Oceanography (SIO), the Department of Meteorology of the University of California, the University of Southern California (USC), the United States Geological Survey, and the U. S. Navy Electronics Laboratory (NEL). Roger Revelle, Acting Director of the Scripps Institution of Oceanography, was scientific leader of the expedition. Russell W. Raitt, SIO (seismic measurements); James N. Snodgrass, SIO (temperature gradients in the bottom mud); Jeffrey D. Frautschy, SIO (bottom cores); Robert S. Dietz, NEL (dredging and underwater photography); K. O. Emery, USC (geological work in the Marshall Islands), and Sidney C. Rittenberg, USC (chemical work on bottom sediments), are but few of the scientists participating.

Observations included radiosonde observations of the upper air, net hauls in the deep scattering layers, currents by the GEK, bottom topography and geology, temperature gradients in the bottom muds, seismic measurements, bottom-sediment chemistry, bacteria in bottom muds, and the usual "classical" oceanographic stations.

New publication in geophysics--Copies of volume 1, number 1, of Meteoros, a "quarterly review of meteorology and geophysics" of the National Meteorological Service of Argentina, have arrived in the United States. The first issue contains six papers bearing on meteorology and one on hydrology, which will be listed in the Bibliography of these Transactions in June. All papers have summaries in English except one, which has a French summary.

New civil engineering series of Carnegie Institute of Technology--A new series, Carnegie Notebooks in Civil Engineering, is being issued by the Civil Engineering Department of the Carnegie Institute of Technology, the purpose of which "is to raise questions, to answer same, to leave others unanswered, and to give selected references for further individual study . . . ." The first is entitled, "The long and short of conduits."

PERSONALIA

James L. Beatty has transferred his activities from the California Division of Highways to the Corps of Engineers, and is connected with the Okinawa Engineer District.

Lloyd V. Berkner, until recently Chairman, Section of Exploratory Geophysics of the Atmosphere of the Department of Terrestrial Magnetism, Carnegie Institution of Washington, has been named President of Associated Universities, Inc., which operate the Brookhaven National Laboratory.

Clarence A. Burmister, Chief of the Radiosonic Laboratory of the U. S. Coast and Geodetic Survey, has been given the Meritorious Service Award of the Department of Commerce.

Sydney Chapman of Queen's College, Oxford, England, who has been on leave for special work at California Institute of Technology, has been named to the Honorary Board of Fellows of the

Geophysical Institute of the University of Alaska. Others on this Board are Jno. A. Fleming, Henry G. Booker, and Merle A. Tuve.

Robert P. Ireland, until recently with the Sacramento District of the Corps of Engineers engaged on exploration of dam sites, has taken up duties as Engineering Geologist with the Military Intelligence Division of the Beach Erosion Board in Washington, D. C.

Stifel W. Jens, a member of the Committee on Infiltration, Section of Hydrology, AGU, has opened an office as a Consulting Engineer in St. Louis, Missouri, with emphasis on hydrologic, hydraulic, and sanitary engineering problems. For the last 18 years he has been associated with Horner and Shifrin, Consulting Engineers, and was a partner in that firm for the last 12 years. One of his major interests is the application of the newer hydrologic knowledge to the determination of surface runoff.

Leonard M. Murphy, Assistant Chief of the Seismology Branch, U. S. Coast and Geodetic Survey, has been given the Meritorious Service Award of the Department of Commerce.

Allen W. Pinger has resigned his full-time position with the New Jersey Zinc Co. at Franklin, New Jersey, and has removed to Salt Lake City, where he will be engaged in consulting geological and geophysical work, continuing part time with the New Jersey Zinc Exploration Co.

Elliott B. Roberts, Chief of the Division of Geophysics, U. S. Coast and Geodetic Survey, has been given the Meritorious Service Award of the Department of Commerce.

Stanley M. McDonald, Chief Geologist and Assistant General Manager, Louisiana Land and Exploration Co., with headquarters in Midland, Texas, died December 11, 1950 at the age of 34. He was born in Macon, Georgia, and took his baccalaureate degree and his degree of Master of Science from Louisiana State University. He served about two years with the State Geologist of Louisiana, a short period with the Kingwood Oil Co., and about a year with the Mineral Board of Louisiana, following which he entered the service of the Louisiana Land and Exploration Co. He had particular talent in combining the viewpoint of the theorist, the practical geologist, and the executive. He had been a member of AGU since 1943.

Harry Richard Seiwell, Oceanographer with the Woods Hole Oceanographic Institution and Consultant of the Office of Naval Research, was killed, together with his wife and two children, when his car collided with a train in a snowstorm at St. Agapit, Quebec, on March 7, 1951. He was born at Hazelton, Pennsylvania, in 1904, and received his baccalaureate degree from the University of North Carolina in 1927. He studied in Oslo and Berlin as a Scandinavian Foundation Fellow, and took the Doctor of Science degree in Oceanography from Massachusetts Institute of Technology in 1938. From 1928 to 1929 he took part in cruises of the Carnegie and was connected with the Buffalo Museum of Science in 1930-1931. He began his work with Woods Hole Oceanographic Institution in 1931, but was on leave during the war years during which he served overseas as a Lieutenant Colonel. He had been a member of AGU since 1932.

Ranbir Singh Shrikant, Engineer for the Government of India on hydrologic and hydraulic projects, died in an accident in India on July 19, 1950. He was born in Hashiapur, East Punjab, India, in 1922, received a diploma as Fellow of Science from the University of Punjab in 1939, and the degree of Bachelor of Science with honors in Civil Engineering in 1942. He came to the United States in 1946, and attended the Graduate Schools of Engineering at the University of Colorado and Harvard University, taking his Master's degree at Harvard in 1948. While in the United States, he also received in-service training with the Bureau of Reclamation. Since his return to India, he has been engaged on various of the great projects involving the rivers of India, with headquarters in New Delhi. He became a member of AGU in 1948.

SPECIAL ANNOUNCEMENT

Ninth General Assembly of the International Union of Geodesy and Geophysics, Brussels, Belgium, August 21-September 1, 1951--Plans are progressing well for this meeting, and the general agenda of the meeting and data on housing have been received from the Belgian Organizing Committee and distributed to the 60 who have indicated their tentative plans to attend. If you plan to go, even tentatively, and you have not yet advised the office of AGU of this, please do so without further delay in order that arrangements for the delegation from the USA proceed and that you may have the information that you require to make your plans.

ADDITIONS TO THE MEMBERSHIP OF THE AMERICAN GEOPHYSICAL UNION, SEPTEMBER 11, 1950 TO MARCH 10, 1951

Adams, Dr. Clifford, P. O. Box 217, Hanover, Ind. (abcdefgh)
Ahlmann, Dr. Hans W., R. Swedish Embassy, Meltzers Gate 4, Oslo, Norway (g)
Albers, Mr. John P., 2646 Russell St., Redding, Calif. (f)
Alexis, Dr. Carl O., Code 416, Office of Naval Research, Washington, 25, D. C. (abcdefgh)
Allen, Mr. William, Jr., P. O. Box 505, Douglas, Ariz. (d)
Anderson, Mr. Charles E., 168 Western Ave., Cambridge 39, Mass. (c)
Anderson, Mr. Richard J., Battelle Memorial Institute, Columbus 1, Ohio (de)
Anderson, Mr. Roland L., P. O. Box 4158, Jacksonville 1, Fla. (c)
Arons, Dr. Arnold, Stevens Institute of Technology, Hoboken, N. J. (ce)
Banks, Mr. Robert B., 508 Coventry Rd., Berkeley 7, Calif. (cg)
Barbour, Mr. Lucius H., P. O. Box 502, Woods Hole, Mass. (ae)
Barnett, Mr. Kenneth M., Scientific Research Div., HICOG, APO 633, c/o Postmaster, New York, N. Y. (c)
Bell, Mr. Gordon B., Jr., 300 Chadbourne Ave., Millbrae, Calif. (c)
Bemis, Mr. Alan C., Nashawtuc Rd., Concord, Mass. (c)
Bennett, Mr. Harvey S., Jr., 7509 Lynn Dr., Chevy Chase 15, Md. (aefgh)
Berg, Mr. Joseph W., Jr., 622 1/2 S. Allen St., State College, Pa. (bh)
Bergstrom, Mr. Stanley W., P. O. Box 271, Woods Hole, Mass. (be)
Berkey, Dr. Donald K., 16 University Ave., Hamilton, N. Y. (d)
Berning, Mr. John, c/o Tsumeb Corp., Ltd., Tsumeb, South West Africa (abdfh)
Bijlaard, Prof. P. P., Lakeland Homes Apts., Unit 3, Ithaca, N. Y. (fh)
Blake, Mr. E. F., 216 N. Big Spring St., Midland, Texas (b)
Blinde, Mr. Glover L., 406 W. Jewell Ave., Denver 10, Colo. (cg)
Bollenbach, Mr. W. M , 2304 Long Ave., St. Paul 4, Minn. (g)
Bowman, Dr. Edgar C., 534 Kelton Ave., Los Angeles 24, Calif. (h)
Brace, Mr. William F., 319 Highland Ave., Winchester, Mass. (fh)
Brown, Mr. Douglas M., 296 Bradley Ave., Meriden, Conn. (fgh)
Brown, Mr. Roy S., 2602 Woodsdale, Lincoln, Nebr. (dg)
Bruet, Dr. E., Laboratoire de Géophysique, St. Claude, Guadeloupe, W. F. I. (fh)
Bucher, Dr. Edwin E., 550 Summit St., St. Paul, Minn. (cg)
Burger, Mr. Pieter, Geological Survey, P. O. Box 401, Pretoria, South Africa (cdg)
Burnham, Mr. Willis Lee, 1022 Harvard Ave., Claremont, Calif. (g)
Bush, Mr. James H., 10725 101st St., Edmonton, Alberta, Canada (bd)
Butler, Mr. Clay P., 738 Sequoia Ave., San Mateo, Calif. (c)
Butler, Dr. John W., Jr., Phillips Oil Co., Apartado 1031, Caracas, Venezuela (bdfh)
Butson, Mr. Keith D., River Forecast Center, U. S. Weather Bureau, 320 Custom House, Portland 9, Ore. (cg)
Byerly, Mr. P. Edward, 6037 Contra Costa Rd., Oakland 18, Calif. (bdeh)
Campbell, Mr. Frank L., 440 Ravenswood St., Menlo Park, Calif. (d)
Campbell, Mr. Richard A., Vidalia, La. (bde)
Carlin, Mr. Palmer W., Physics Dept., University of Colorado, Boulder, Colo. (bc)
Carter, Mr. Douglas B., Laboratory of Climatology, Johns Hopkins University, Seabrook, N. J. (cg)
Chidester, Mr. Alfred H., 7 Winter St., Montpelier, Vt. (fh)
Cohick, Mr. Kenneth S., 3436 Stanbridge Ave., Long Beach 8, Calif. (bdh)
Coman, Dr. Dana, Research Branch, GSUSA, Washington 25, D. C. (c)
Copeland, Mr. Harold L., Creole Petroleum Corp., Apt. 889, Caracas, Venezuela (bh)
Corn, Miss Joyce C., 5727 University Ave., Chicago, Ill. (c)
Cornelison, Mr. Boyd, 2424 Branard St., Houston 6, Texas (ah)
Coster, Dr. H. P., Seismograph Service, Ltd., 3A, London Wall Bldg., London, E. C. 2, England (b)
Coulter, Prof. Richard G., Cooper Union for the Advancement of Science and Arts, Cooper Square, New York, N. Y. (g)
Covey, Mr. Winton, 926 Montpelier St., Baltimore 18, Md. (cg)
Croft, Mr. Marshall S., 608 Pine St., Teague, Texas (c)
Cross, Mr. James Harvey, P. O. Box 1946, University Sta., Austin 12, Texas (bdfh)
Dangberg, Miss Grace M., Minden, Nev. (cg)
Davis, Mr. John J., 527 U. S. Courthouse, Ft. Worth, Texas (c)

de Carvalho, Dr. Gaspar Soares, Rua do Alto da Conchada 33, Coimbra, Portugal (eg)
Dehlinger, Dr. Peter, Battelle Memorial Institute, 505 King Ave., Columbus 1, Ohio (abch)
Dengo, Dr. Gabriel, Instituto Nl. de Minería y Geología, Ministerio de Fomento, Caracas, Venezuela (fh)
de Quervain, Dr. Marcel R., Davos-Dorf, Switzerland (g)
Dibble, Mr. Edward Fitzgerald, 107 Garden Hill, Redlands, Calif. (cdg)
Doeglas, Dr. D. J., Laboratorium voor Minéralogie en Geologie, Wageningen, The Netherlands (eg)
Doran, Mr. Floyd J., 3831 Stockbridge Ave., Los Angeles, Calif. (cg)
Downey, Mr. Hugh P., Weiss Geophysical Corp. of Canada, Greyhound Bldg., Calgary, Alberta, Canada (abdefh)
Dreimanis, Mr. Aleksis, 43 Evergreen Ave., London, Ont., Canada (fgh)
Duba, Mr. John G., Civil Engineering Dept., Illinois Institute of Technology, Chicago, Ill. (g)
Eddards, Mr. Miles L., Jr., 348 S. 10th St., Baton Rouge, La. (g)
Etheridge, Mr. Kirby E., P. O. Box 251, Columbus, Texas (b)
Farmer, Mr. Harlow G., Woods Hole Oceanographic Institution, Woods Hole, Mass. (eg)
Ferrell, Mr. William R., U. S. Geological Survey, 215 Federal Bldg., San Bernardino, Calif. (g)
Fickinger, Mr. D. E., Continental Oil Co., Ponca City, Okla. (b)
Finnell, Mr. Tommy L., Dept. of Geology, University of Wyoming, Laramie, Wyo. (abfgh)
Fitzpatrick, Mr. Michael, 1727 Cambridge St., Cambridge, Mass. (abdfh)
Floyd, Maj. Percy M , Jr., Laboratory of Climatology, Johns Hopkins University, Seabrook, N. J. (c)
Focke, Dr. Alfred B., 5110 Alta Vista St., San Diego 9, Calif. (bcde)
Folsom, Mr. T. R., Scripps Institution of Oceanography, La Jolla, Calif. (e)
Friedman, Mr. Gerald M., Dept. of Geology, University of Cincinnati, Cincinnati, Ohio (f)
Fuller, Mr. William R., U. S. Weather Bureau, Hartford 6, Conn. (g)
Gain, Mr. Elmer W., 337 Sagamore Rd., Havertown, Pa. (g)
Gauthier, Mr. Paul G., 5126 Park Ave., Montreal 8, P.Q., Canada (ab)
Goldberg, Dr. Edward D., Scripps Institution of Oceanography, La Jolla, Calif. (ae)
Gornitzky, Mr. Raymond, 6807 Riggs Rd., Hyattsville, Md. (a)
Gragnon, Mr. Joseph N., P. O. Box 2061, San Antonio, Texas (b)
Gulf Research and Development Co., P. O. Drawer 2038, Pittsburgh 30, Pa. (Corp. Member, Dr. Leo J. Peters, representative)
Hackett, Mr. James E., 209 Wisconsin Ave., Madison, Wis. (g)
Hanson, Mr. Earl P., 201 Haines St., Newark, Del. (de)
Hardison, Mr. Stanley G., P. O. Box 337, Sunray, Texas (bdh)
Harris, Mr. D. B., 1400 N.W. 23rd St., Oklahoma City, Okla. (b)
Harris, Mr. Robert A., Weather Station, Griffiss AFB, Rome, N. Y. (bc)
Haupt, Lt. (jg) Richard W., USN, U.S.S. Maury, (AGS-16), FPO, New York, N. Y. (ade)
Henderson, Mr. Thomas J., 2845 1/2 Cabrillo St., San Francisco 21, Calif. (cg)
Herlihy, Mr. Daniel E., P. O. Box 236, Aztec, N. Mex. (abd)
Higgs, Mr. Jere Will, Jr., 5937 Burgundy St., Baton Rouge, La. (g)
Hilton, Mr. Richard C., P. O. Box 2099, Houston 1, Texas (bdh)
Hiser, Mr. Homer Wendell, 602 E. Stoughton St., Champaign, Ill. (cg)
Holland, Dr. Heinrich D., Geology Dept., Princeton University, Princeton, N. J. (f)
Holm, Mr. Donald A., 49 Humphrey Rd., Santa Barbara, Calif. (abcefgh)
Holmes, Mr. O. M., P. O. Box 113, Strong, Ark. (bd)
Hornstein, Mr. R. A., P. O. Box 653, Halifax, N. S., Canada (c)
Hotes, Prof. Frederick L., Apt. 5, 6506 Glenmore Dr., Falls Church, Va. (cg)
Hunter, Mr. William R., 315 N. MacArthur Ave., Panama City, Fla. (acd)
Ingebo, Mr. Paul, 1407 Jackson St., Missoula, Mont. (g)
Institute of Geophysics, University of California, Los Angeles 24, Calif. (Corp. Member; Prof. L. B. Slichter, representative)
Irby, Mr. W. L., 1229 1/2 S. 18th St., Terre Haute, Ind. (ab)
Isaacs, Mr. John D., 205 Fifth Ave., Encinitas, Calif. (ed)
Johnson, Dr. Montgomery H., 1001 Potomac Ave., Alexandria, Va. (d)
Jorissen, Dr. Andre L., Dept. of Civil Engineering, Pennsylvania State College, State College, Pa. (eg)
Katz, Mr. Robert, 3100 Brighton 2nd St., Brooklyn 35, N. Y. (bd)
Katz, Mr. Seymour, 3100 Brighton 2nd St., Brooklyn 35, N. Y. (bd)
Katzenstein, Dr. J., P. O. Box 152, College, Alaska (d)
Kilkenny, Mr. John E., Union Oil Co., 1115 Union Oil Bldg., 617 W. 7th St., Los Angeles 17, Calif. (bdh)
Kindle, Prof. Cecil H., City College of New York, New York 31, N. Y. (egh)
Krahl, Mr. George M., 7612 Gateway Blvd., District Heights, Washington 19, D. C. (cg)
Krinitzsky, Dr. Ellis L., Apt. 416, 538 Saint Peter St., St. Paul, Minn. (abcg)
Krumm, Mr. Tahlman, 65 Meadow Park Rd., Columbus 9, Ohio (g)
Lahlum, Lt. Col. Arthur H., 53 N. Dunlap St., St. Paul 5, Minn. (g)

Lamoreux, Mr. Wallace W., U. S. Weather Bureau, 501 Federal Bldg., Salt Lake City 1, Utah (cg)
Lee, Mr. Robert E., Lee Geophysical Expl. and Research Corp., P. O. Box 632, Cisco, Texas (abdfh)
Leinbach, Mr. Harold, Jr., P. O. Box 101, College, Alaska (d)
Leith, Mr. Thomas H., Room 24-007, Mass. Institute of Technology, Cambridge, Mass. (h)
Little, Prof. Edward M., Physics Dept., University of Alaska, College, Alaska (cdgh)
Loeb, Prof. Leonard B., Dept. of Physics, University of California, Berkeley 4, Calif. (cd)
Longard, Mr. John R., Naval Research Establishment, Halifax, N. S., Canada (e)
Machta, Dr. Lester, 1202 Mississippi Ave., S.E., Washington 20, D. C. (c)
MacLeod, Mr. George M., Fisher Research Lab., Inc., P. O. Box 640, Palo Alto, Calif. (bg)
Magnuson, Mr. Marvin D., 3108 Carpenter Ave., Des Moines, Iowa (c)
Maher, Comdr. E. H., OPNAV 342, Navy Dept., Washington 25, D. C. (e)
Maher, Mr. Fred R., 3317 Ralston Ave., Indianapolis, Ind. (cdeg)
Manning, Dr. John C., Dept. of Geology, Stanford University, Stanford, Calif. (g)
Marable, Mr. James R., 1537 Ava Pl., Decatur, Ga. (bg)
Mason, Mr. Arnold C., Engr. Sec., GHQ, FEC, APO 500, San Francisco, Calif. (g)
Masson, Mr. Peter H., 5418 Austin St., Houston 4, Texas (fh)
Mather, Mr. John R., Dept. of Geography, Johns Hopkins University, Baltimore 18, Md. (c)
Mathews, Mr. Ted C., P. O. Box 2061, Fairbanks, Alaska (bcgh)
McCahan, Mr. A. L., 1718 Ft. Davis St., S.E., Washington 20, D. C. (adeg)
McDowell, Prof. D. Clay, University of Puerto Rico, Río Piedras, P. R. (c)
McLellan, Mr. Hugh J., St. Andrews, New Brunswick, Canada (e)
Miller, Prof. John P., Dept. of Earth Sciences, Pennsylvania State College, State College, Pa. (fg)
Miller, Mr. Maynard M., Dept. of Expl. and Field Research, American Geographical Society, Broadway and 156th St., New York 32, N. Y. (g)
Misener, Prof. A. D., University of Western Ontario, London, Canada (dh)
Mock, Mr. Clyde, 123 Kelley St., Modesto, Calif. (b)
Moran, Mr. Robert B., Jr., 3328 Martha Circle, Pasadena 10, Calif. (bdh)
Morriss, Mr. Herbert A., Jr., 428 Albany Ave., Shreveport 20, La. (dh)
Moses, Mr. Harry M., 10 W. Churchill St., Stockton, Calif. (cg)
Moses, Dr. John H., Cerro de Pasco Copper Co., La Oroya, Peru (acfgh)
Murphy, Mr. Alvin D., 1171 Utah St., S.E., Huron, S. Dak. (c)
Newport, Mr. Thomas G., P. O. Box 205, Ainsworth, Nebr. (gh)
Nichols, Mr. Roger C., U. S. Weather Bureau, 219-A Custom House, San Francisco 11, Calif. (c)
Nizery, Mr. A., 20 Rue Eugene Manuel, Paris 16^{e}, France (eg)
Oliver, Mr. Howard W., 201 William James, Harvard University, Cambridge 38, Mass. (abdeh)
Olmsted, Prof. Elizabeth W., 119 Prospect Ave., Northampton, Mass. (gh)
Panay, Dr. T. Nicholas, Burlington Hotel, Washington 5, D. C. (d)
Paquette, Dr. Robert G., 6234 51st N.E., Seattle 5, Wash. (e)
Parker, Mr. Herbert, Sun Oil Co., Beaumont, Texas (bdh)
Parson, Mr. Donald, Jr., P. O. Box 719, Osterville, Mass. (cde)
Patterson, Mr. Samuel O., 735 Eighth Ave., West, Calgary, Alberta, Canada (b)
Postma, Dr. G. W., 4419 Philstreet, Bellaire, Texas (bdh)
Rattray, Dr. Maurice, Jr., Oceanographic Lab., University of Washington, Seattle 5, Wash. (e)
Raudsepp, Mr. Valter, Water Rights Branch, Parliament Bldgs., Victoria, B.C., Canada (g)
Rector, Mr. Ralph L., 10417 Manakee St., Kensington, Md. (eg)
Reid, Mr. Joseph L., Jr., 7814 Bishops Lane, La Jolla, Calif. (e)
Richey, Mr. Joseph L., Oaklynne, Princeton Jct., N. J. (cd)
Riley, Dr. Gordon A., Bingham Oceanographic Lab., Yale University, New Haven, Conn. (e)
Roberson, Mr. John A., 507 Oak St., Pullman, Wash. (g)
Robertson, Mr. Eugene C., Dept. of Geology, Harvard University, Cambridge 38, Mass. (h)
Robley, Mr. Grant, 988 Yale Station, New Haven, Conn. (cg)
Rockney, Mr. Vaughn D., 4936 Baltimore Ave., Washington 16, D. C. (c)
Root, Mr. James A., 105 Highland Pl., Ithaca, N. Y. (ag)
Rosen, Mr. Maurice, 1008 St. Parks Ave., Brooklyn 13, N. Y. (bcdh)
Rosenau, Mr. Edgar N., Meteorological Service, Ministry of Transport and Communications, Hakiriya, Israel (ceg)
Rudnick, Dr. Philip, 405 Vincente Way, La Jolla, Calif. (e)
Rulison, Mr. John G., 203 Capitol Savings and Loan Bldg., Lansing 68, Mich. (cg)
Sandell, Dr. Ernest B., School of Chemistry, University of Minnesota, Minneapolis, Minn. (f)
Sanderson, Dr. James O. G., 219 Lougheed Bldg., Calgary, Alberta, Canada (befh)
Sangster, Prof. William M., Dept. of Civil Engineering, University of Missouri, Columbia, Mo. (cg)
Sarquis, Mr. Armen V., 1238 Douglas Rd., Stockton, Calif. (cg)
Saull, Mr. Vincent, 305 Memorial Dr., Cambridge, Mass. (bf)
Savage, Mr. C. N., 819 Morris Rd., Kent, Ohio (dfgh)
Schad, Mr. Theodore M., 3000 Gainsville St., S.E., Washington 20, D. C. (g)
Schaub, Maj. Ward K., 312 Fairmont St., Falls Church, Va. (fh)

Schnittker, Mr. Fred B., P. O. Box 352, Barksdale Air Force Base, La. (a)
Schreurs, Mr. Raymond L., 3803 S. 44th St., Lincoln 6, Nebr. (dgh)
Sherman, Capt. Wm. H., Army Map Service, Rm. 500, 6400 Brooks Lane, Washington, D. C. (aeg)
Shor, Mr. George G., Jr., P. O. Box 459, Orange, Texas (b)
Shrock, Prof. Robert R., Room 24-302, Mass. Institute of Technology, Cambridge 39, Mass. (efgh)
Slack, Mr. Howard A., Dept. of Geology, Northwestern University, Evanston, Ill. (f)
Slaughter, Mr. George M., School of Hydraulic Engineering, Louisiana State University, Baton Rouge, La. (g)
Smith, Mr. Paul F., St. Park's School, Southboro, Mass. (e)
Smith, Mr. Raymond J., Dept. of Geology, Princeton University, Princeton, N. J. (h)
Staley, Mr. Raymond C., E. D. Hall 101, University of Texas, Austin 12, Texas (c)
Stallman, Mr. Robert W., General Delivery, Sterling, Va. (g)
Stevenson, Mr. Robert E , 723 W. Palmer Ave., Compton 4, Calif. (e)
Stewart, Mr. Francis, 967 E. 36th St., Tulsa, Okla. (b)
Stone, Mr. Newton C., 214 S. Wilson Ave., Pasadena 5, Calif. (c)
Sucre A., Dr. Oscar Alberto, Avenida Este No. 124, Caracas, Venezuela (cg)
Switzer, Dr. George S., U. S. National Museum, Washington 25, D. C. (f)
Tator, Dr. Benjamin A., School of Geology, Louisiana State University, Baton Rouge, La. (cd)
Taylor, Mrs. Eloise W., 3730 Hayes St., N.E., Washington 19, D. C. (d)
Teague, Mr. Norman P., Apartado 463, Caracas, Venezuela (agh)
Thompson, Prof. Henry D., Hunter College, 695 Park Ave., New York 21, N. Y. (ah)
Thompson, Dr. James B., Jr., Dept. of Mineralogy, Harvard University, Cambridge 38, Mass. (fh)
Thorp, Mr. N. D., Okanogan Irrigation District, Okanogan, Wash. (cdg)
Tocher, Mr. Don, Seismographic Station, University of California, Berkeley 4, Calif. (b)
Uffen, Mr. Robert J., Dept. of Physics, University of Western Ontario, London, Ont., Canada (dh)
Vos, Mr. H., Dominion Gulf Co., P. O. Box 281, Larder Lake, Ont., Canada (bdh)
Wadati, Dr. Kiyoo, Central Meteorological Observatory, Chiyodaku, Tokyo, Japan (bc)
Wagoner, Mr. George F., 1020 Anniston St., Shreveport, La. (bcd)
Wahlstrom, Prof. Ernst E., Dept. of Geology, University of Colorado, Boulder, Colo. (fh)
Walker, Mr. George W., 231 Gordon Way, Los Altos, Calif. (abfh)
Walling, Mr. I. W., U. S. Geological Survey, c/o University of California, 126 Irrigation Dept., Davis, Calif. (g)
Wandke, Mr. Alfred D., P. O. Box 1512, Prescott, Ariz. (fh)
Watson, Mr. Frank H., Jr., P. O. Box 61, Lodi, Calif. (cg)
Weickmann, Dr. Helmut, Bowne Rd., RD No. 1, Asbury Park, N. J. (cdg)
Weisbord, Mr. Norman E., Apartado 246, Caracas, Venezuela (acefg)
White, Mr. French R., Puenticitas Oil Co., Kaffie Bldg., Corpus Christi, Texas (abcdefgh)
White, Mr. Sidney E., Dept. of Geology, Syracuse University, Syracuse 10, N. Y. (cefg)
Willett, Mr. James H., 3105 Parkway Terrace Dr., Apt. 6, Washington 20, D. C. (aeh)
Wilson, Mr. James E., P. O. Box 7, College, Alaska (bd)
Wilson, Prof. Thomas V., Agricultural Eng. Bldg., North Carolina State College, Raleigh, N. C. (g)
Wilson, Dr. William S., P. O. Box 13, College, Alaska (cd)
Wolfe, Dr. Caleb W., 725 Commonwealth Ave., Boston 15, Mass. (befgh)
Wolman, Mr. M. Gordon, Dept. of Geology, Harvard University, Cambridge, Mass. (g)
Wood, Mr. F. W., 14 Bates Rd., Arlington 74, Mass. (bd)
Woods, Dr. J. P., 3629 Cragmont St., Dallas 5, Texas (b)
Worden, Mr. Sam, 2424 Branard St., Houston 6, Texas (a)
Wortz, Mr. Carl H., III, Wortz Biscuit Co., Fort Smith, Ark. (c)
Yahn, Mr. William J.. 112 N. Clinton St., Olean, N. Y. (h)
Yih, Prof. Chia-shun, Civil Eng. Dept., Colorado A. and M. College, Fort Collins, Colo. (acg)
Young, Mr. W. Ray, 1325 Park Ave., Abilene, Texas (abegh)
Younkin, Mr. Russell J., 1512 Garfield St., Alcoa, Tenn. (cg)
Zinszer, Dr. Richard H., 505 Park Ave., New York, N Y. (bdfgh)
Zuidema, Mr. Henry P., 130 Lawrence Ave., Detroit 2, Mich. (e)
Zvonar, Capt. Stephen, 91st Reconnaissance Tech. Sq., Barksdale Air Force Base, La. (a)

Transferred from Inactive to Active Status

Erickson, Mr. John R., 6 Pueblo Dr., Santa Fe, N. Mex. (g)
Faust, Dr. L. Y., P. O. Box 2040, Tulsa 2, Okla. (b)
Fletcher, Dr. Peter W., Dept. of Forestry, College of Agriculture, University of Missouri, Columbia, Mo. (g)
Grover, Mr. George M., 2992-C, Gold St., Los Alamos, N Mex. (c)
Hardman, Prof. George, State Coordinator, Soil Conservation Service, University of Nevada, Reno, Nev. (c)
Maddock, Mr. Thomas, Jr., U. S. Bureau of Reclamation, Washington 25, D. C. (g)
Stapp, Mr. Wilford L., Survey Oil Co., P. O. Box 231, Abilene, Texas (a)

GEOPHYSICAL RESEARCH CORPORATION

Geophysical Prospecting
Application of Geophysical Methods in the Petroleum Industry

2607 North Boston Place
Tulsa 6, Oklahoma

GULF RESEARCH & DEVELOPMENT COMPANY
GULF OIL CORPORATION

Geophysical and Other Research
Relating to the Petroleum Industry

P. O. Drawer 2038
Pittsburgh 30, Pennsylvania

INSTITUTE OF GEOPHYSICS

UNIVERSITY OF CALIFCRNIA

Los Angeles 24, California

RANNEY METHOD WATER SUPPLIES, INC.

Ground Water Exploration and Development

841 Alton Avenue
Columbus 3, Ohio

RUSKA INSTRUMENT CORPORATION

Developers, Designers, and Manufacturers of Instruments for Field and Observatory Use
Magnetic, Geodetic, Seismic, and Meteorological Work

4607 Montrose Boulevard
Houston 6, Texas

SEISMOGRAPH SERVICE CORPORATION

Seismic Exploration Service for
Oil and Gas Structures throughout the World

P. O. Box 1590
Kennedy Building
Tulsa 1, Oklahoma

SPRENGNETHER INSTRUMENT COMPANY

Manufacturer of Seismological and Geophysical Instruments
Instrumental Development and Research

4567 Swan Avenue
St. Louis 10, Missouri

NATIONAL RESEARCH COUNCIL
of the
NATIONAL ACADEMY OF SCIENCES

PROGRAM

THIRTY-SECOND ANNUAL MEETING

In the Building of the National Research Council - National Academy of Sciences,
and the Auditorium of the General Services Building,
Washington, D. C.

April 30 - May 2, 1951

SCHEDULE OF SESSIONS

Monday, April 30, 1951

09h 00m OCEANOGRAPHY- Room 3 VOLCANOLOGY--Room 2
HYDROLOGY--Room 1
14h 00m SEISMOLOGY--Room 2 OCEANOGRAPHY--Room 1
TERRESTRIAL MAGNETISM AND ELECTRICITY--Room 3
20h 00m EVENING SESSION (First Session of Symposium on the Measurement of Geologic Time, Award of the William Bowie Medal, Social Hour)--Room 2

Tuesday, May 1, 1951

09h 00m SEISMOLOGY--Room 2 METEOROLOGY--Room 1
HYDROLOGY--Room 3
14h 00m METEOROLOGY--Room 3 HYDROLOGY--Room 1
TERRESTRIAL MAGNETISM AND ELECTRICITY--Room 2
20h 00m SMOKER--Auditorium of the Cosmos Club, Madison Place near H Street, Northwest

Wednesday, May 2, 1951

09h 00m GEODESY--Room 1 TECTONOPHYSICS--Room 2
14h 00m GENERAL ASSEMBLY (Second Session of Symposium on the Measurement of Geologic Time, and Business Session)--Room 1

(For key to room numbers, see page 312)

OFFICERS OF THE UNION

John A. Fleming, Honorary President

Walter H. Bucher, President	F. W. Reichelderfer, Vice President
K. Hilding Beij, General Secretary	Waldo E. Smith, Executive Secretary

COMMITTEE ON MEETINGS

J. P. Marble, Chairman

J. A. Duerksen	Nicholas A. Rose	O. W. Torreson
Merle A. Tuve	Frank J. Veihmeyer	George G. West

(Note: This program is paginated in the Transactions of 1951. Preserve for binding.)

OFFICERS OF THE SECTIONS

Section	President	Vice President	Secretary
Geodesy	Harry H. Hess	A. J. Hoskinson	Frank L. Culley
Seismology	Perry Byerly	L. M. Murphy	James T. Wilson
Meteorology	Benjamin Holzman	Hurd C. Willett	Woodrow C. Jacobs
Terrestrial Magnetism and Electricity	J. W. Joyce	Victor Vacquier	L. R. Alldredge
Oceanography	A. C. Redfield	Roger R. Revelle	R. H. Fleming
Volcanology	Esper S. Larsen, Jr.	Thomas P. Thayer	Felix Chayes
Hydrology	F. J. Veihmeyer	Merrill Bernard	Ray K. Linsley
Tectonophysics	Robert Balk	Francis Birch	Wilbur S. Burbank

GENERAL MEETINGS OF THE UNION

EVENING SESSION

Monday, April 30, 1951, 20h 00m, Room 2 (Lecture Room, National Academy of Sciences)

Symposium on the Measurement of Geologic Time - First Session
- (1) JOHN PUTNAM MARBLE: Introduction (5 minutes)
- (2) RAYMOND C. MOORE: Stratigraphic viewpoints in measurement of geologic time (20 minutes)
  Discussion (10 minutes)
- (3) EDWARD McCRADY: The use of lead isotopic ratios in age determinations (20 minutes)
  Discussion (10 minutes)

(Second session of Symposium will be held Wednesday afternoon, May 2, 1951, immediately preceding the Business Meeting)

Thirteenth Award of the William Bowie Medal
- (a) Citation
- (b) Presentation by Walter H. Bucher
- (c) Acceptance

Social hour and refreshments

SMOKER

Tuesday, May 1, 1951, 20h 00m to 22h 00m, Auditorium of the Cosmos Club, Madison Place near H Street, Northwest

This will be an informal gathering with no planned program. Refreshments will be served. Tickets are 75 cents, and will be sold in advance at the Main Registration Desk in the Building of the National Research Council - National Academy of Sciences, and by the Secretaries of the Sections. Ladies are invited. These gatherings have been very well accepted in previous years, as they offer opportunity to get together very informally with old and new acquaintances, and to make new acquaintances.

GENERAL ASSEMBLY
SECOND SESSION OF THE SYMPOSIUM, AND BUSINESS MEETING

Wednesday, May 2, 1951, 14h 00m, Room 1 (Auditorium, National Academy of Sciences)

Symposium on the Measurement of Geologic Time - Second Session
- (4) F. H. H. ROBERTS, JR.: Carbon 14 dates and archeology (20 minutes)
  Discussion (10 minutes)
- (5) P. M. HURLEY: Helium retentivity versus alpha activity in zircon and sphene (20 minutes)
  Discussion (10 minutes)
- (6) J. L. KULP: Progress report on age work at Lamont Geological Observatory (20 minutes)
  Discussion (10 minutes)
- (7) L. H. AHRENS: Some newer developments of the strontium method applied to lepidolite and biotite, and the feasibility of a calcium method (20 minutes)
  Discussion (10 minutes)

Business Meeting (Effort will be made to keep this within our usual half hour)
(1) Reports of officers and of special and standing committees, including:
(a) General Secretary's report
(b) Report of the Committee on Resolutions (Mary C. Rabbitt, Chairman; Werner A. Baum, and Francis G. Wells)
(2) Unfinished business
(3) New business

MEETINGS OF THE SECTIONS

SECTION OF GEODESY

Wednesday, May 2, 1951, 09h 00m, Room 1 (Auditorium, National Academy of Sciences)

Business Session
Reports of committees and other business
Scientific Session
(1) WARREN D. FORRESTER: A discussion of the accuracy required in astronomic determinations for Laplace azimuth control
(2) J. A. O'KEEFE and J. S. McCALL: A proposed method for long-distance traverse
(3) JULIUS L. SPEERT: Radar altimetry operations of the United States Geological Survey in 1950
(4) MANUEL MEDINA: The geodetic work in Mexico from May 1950 to April 1951
(5) W. HEISKANEN: Recent progress in geophysical geodesy
(6) G. D. GARLAND: Gravity measurements in the Maritime Provinces of Canada
(7) J. L. WORZEL and MAURICE EWING: Gravity measurements at sea, 1950
(8) G. P. WOOLLARD: The development of the world gravimeter network to date
(9) HOWARD S. RAPPLEYE: Precision leveling at the White House

SECTION OF SEISMOLOGY

Monday, April 30, 1951, 14h 00m, Room 2 (Lecture Room, National Academy of Sciences)

Business Session
Reports of committees and other business
Scientific Session
(1) WILLIAM L. DONN: Observations bearing on the origin and propagation of microseisms (20 minutes)
(2) DANIEL J. O'HALLORAN: A microseismic study of cold-front passage over inland bodies of water (20 minutes)
(3) JOSEPH LYNCH: Fordham's new tripartite station at Poughkeepsie, New York (15 minutes)
(4) H. BENIOFF, B. GUTENBERG, and C. F. RICHTER: Progress report, Seismological Laboratory, California Institute of Technology, 1950 (20 minutes)

Tuesday, May 1, 1951, 09h 00m, Room 2 (Lecture Room, National Academy of Sciences)

(5) FRANK PRESS, A. P. CRARY, JACK OLIVER, and S. KATZ: Air-coupled flexural waves in floating ice (15 minutes)
(6) M. A. TUVE, H. E. TATEL, and L. H. ADAMS: Coherent explosion wave patterns at 100 kilometers (15 minutes)
(7) H. E. TATEL, M. A. TUVE, and L. H. ADAMS: Crustal structures indicated by explosion wave patterns (10 minutes)
(8) MILTON B. DOBRIN, R. F. SIMON, and P. L. LAWRENCE: Rayleigh waves from small explosions (20 minutes)
(9) PETER DEHLINGER: Shear-wave vibrational directions and related fault movements in Southern California earthquakes (10 minutes)
(10) P. G. GANE: Rockburst seismology in South Africa (10 minutes)

SECTION OF METEOROLOGY

Tuesday, May 1, 1951, 09h 00m, Room 1 (Auditorium, National Academy of Sciences)

Business Session

Reports of committees and other business

Scientific Sessions

(1) WILLIAM C. SPREEN and NICHOLAS MANOS: Probabilities from limited weather data (20 minutes)
(2) GEORGE L. ARNOLD: Relation between cloud cover and cloud height (20 minutes)
(3) WALTER HITSCHFELD: Free fall of drops through the air (20 minutes)
(4) PATRICIA A. LANGWELL: The onset of rain from cumulus (by title)
(5) L. L. WEISS: Moisture accumulation rates in thunderstorm cells (20 minutes)
(6) W. H. WYATT: Daily fluctuations of the Arctic inversion (20 minutes)
(7) RONALD L. IVES: Recurrent mirages at Puerto Peñasco, Sonora (10 minutes)

Tuesday, May 1, 1951, 14h 00m, Room 3 (Auditorium, General Services Building)

(8) PHILIP F. CLAPP: Kinematic vortex theory applied to the motion of anomalies of the general circulation (20 minutes)
(9) SEYMOUR L. HESS: The effect of the general circulation on the latitudinal and temporal distribution of temperature (20 minutes)
(10) THOMAS A. GLEESON: On the theory of cross-valley winds arising from differential heating of the slopes (20 minutes) (to be read by Werner A. Baum)
(11) JOANNE STARR MALKUS and MELVIN E. STERN: Airflow over a heated island (15 minutes) (to be presented by Mr. Stern)
(12) LEWIS D. KAPLAN: The pressure dependence of radiative heat transfer (20 minutes)
(13) WILLIAM S. WILSON, W. G. GUENTHER, ROBERT D. LOWREY, and JOSEPH C. CAIN: Concentration of surface ozone at College, Alaska, for the year 1950 (20 minutes)

(Note: Sessions of the American Meteorological Society will begin Wednesday morning, May 2, 1951, in the Auditorium of the Natural History Building of the National Museum at Tenth Street and Constitution Avenue, and continue through Friday, May 4, 1951. In arranging the above program and that of the American Meteorological Society, some papers transmitted to the American Geophysical Union for its program have been transferred to the program of the American Meteorological Society, in the interests of unity of program content. Likewise, some papers sent for the program of the American Meteorological Society have been transferred to the program above.)

SECTION OF TERRESTRIAL MAGNETISM AND ELECTRICITY

Monday, April 30, 1951, 14h 00m, Room 3 (Auditorium, General Services Building)

Business Session

Reports of committees and other business

Scientific Sessions

(1) RALPH J. HAVENS: Atmospheric pressure and density to 160 kilometers (10 minutes)
(2) T. R. BURNIGHT: Soft X-ray intensities measured in the upper atmosphere (10 minutes)
(3) M. H. JOHNSON: Electric and magnetic fields about a rocket (10 minutes)
(4) M. J KOOMAN, D. M. PACKER, R. SCOLNIK, and E. O. HULBURT: Measurements of the brightness of the twilight sky (10 minutes)
(5) RENEE HERMAN and LOUIS HERMAN: New band systems of nitrogen in the spectrum of the aurora (10 minutes) (to be read by W. S. Wilson)
(6) H. W. WELLS: Characteristics of local ionospheric disturbances (15 minutes)
(7) REYNOLD GREENSTONE: Systematic ionospheric winds (10 minutes)
(8) DONALD M. SWINGLE: Some observations of the bright-band radio echo (15 minutes)
(9) JULES AARONS: Low-frequency noise (10 minutes)
(10) GEORGE O'DONNELL: A comparative study of the electric conductivity of the air at the ground and at one meter above ground (by title)

Tuesday, May 1, 1951, 14h 00m, Room 2 (Lecture Room, National Academy of Sciences)

(11) OSCAR WEISS: Abnormal magnetic polarization of faulting in Lower Witwatersrand Shales in the Union of South Africa (15 minutes)
(12) FRED KELLER, JR., L. S. BAKER, and B. C. BYRNES: Airborne magnetic operations (15 minutes)
(13) ELLIOTT B. ROBERTS: Punch-card processing of geomagnetic work (5 minutes)
(14) PATRICK L. O'DEA and H. HERBERT HOWE: Six additional years of spontaneous increase in magnetic moment (10 minutes)
(15) DAVID G. KNAPP: Reversible susceptibility and the induction factor used in geomagnetism (10 minutes)
(16) R. E. GEBHARDT, T. J. HINCKLEY, and T. L. SKILLMAN: A photoelectric magnetograph (10 minutes)
(17) ROBERT WARREN LONG: Magnetic observatory at the University of Houston (10 minutes)
(18) E. J. CHERNOSKY: The variation of the geomagnetic activity recurrence interval with the solar cycle (10 minutes)
(19) C. GAIBAR PUERTAS: Increase of the Earth's magnetism (10 minutes)
(20) ELLIOTT B. ROBERTS: Current magnetic work of the United States Coast and Geodetic Survey (by title)
(21) H. FREEBORN JOHNSTON: Recent annual magnetic values at world-wide observatories (by title)

SECTION OF OCEANOGRAPHY

Monday, April 30, 1951, 09h 00m, Room 3 (Auditorium, General Services Building)

Business Session

Reports of committees and other business

Scientific Sessions

(1) W. ARMSTRONG PRICE: The status of geological oceanography in the United States
(2) C. W. THOMAS: Physical and biological investigations in the Bering Sea and portions of the Arctic Ocean, 1948 (15 minutes)
(3) J. R. LONGARD and R. E. BANKS: Wind-induced vertical movement of the water on an open coast (15 minutes) (to be presented by Mr. Longard)
(4) A. R. MILLER: Some notes on the computation of dynamic topography in shallow water
(5) W. H. MUNK: Note on the dynamics of the Antarctic Circumpolar Current (15 minutes)
(6) WILLIAM S. von ARX: Surface velocities in the Gulf Stream (10 minutes)
(7) W. N. BASCOM: Relationship between sand size and beach face slope
(8) JOHN C. AYRES, DEAN F. BUMPUS, and ALFRED C. REDFIELD: The fresh-water exchange of Great South Bay, Long Island (10 minutes) (to be presented by Mr. Redfield)
(9) W. N. BASCOM: Relationship between ocean swell and water temperature and beach width

Monday, April 30, 1951, 14h 00m, Room 1 (Auditorium, National Academy of Sciences)

(10) SIDNEY H. UPHAM: The electrical wave staff - a deep-sea wave measuring instrument (10 minutes)
(11) DALE F. LEIPPER: Progress in oceanography at Texas A. and M. College
(12) I. I. SCHELL: The problem of the iceberg population in Baffin Bay and Davis Strait and advance estimate of the berg count off Newfoundland (15 minutes)
(13) RICHARD JAMES: A test of wave forecasting methods applied to Long Branch, New Jersey (15 minutes)
(14) WILLARD J. PIERSON, JR.: The propagation of a finite wave train in infinitely deep water (15 minutes)
(15) S. E. RAUCH: Introductory theory for a Rayleigh disc wave direction indicator
(16) FRANK MacDOUGAL: Correlation of heights of observed and computed local wind waves in North Atlantic Ocean and Mediterranean Sea (15 minutes)
(17) J. W. JOHNSON and J. R. MORISON: The damping action of submerged breakwaters (by title)

SECTION OF VOLCANOLOGY

Monday, April 30, 1951, 09h 00m, Room 2 (Lecture Room, National Academy of Sciences)

Business Session

Discussion of proposed change of name of Section

Reports of committees and other business

Scientific Session

(1) E. G. ZIES: Volcanic activity at Santiaguito, 1932-40; a geochemical study (20 minutes)

(2) HOWEL WILLIAMS: The great eruption of Coseguina, Nicaragua, in 1835 (10 minutes)

(3) KENZO YAGI: Formation of Syowa Sinzan, a new volcano in Japan (15 minutes)

(4) R. E. WILCOX: Progressive changes in chemical composition of Parícutin lavas (10 minutes) (to be read by Francis Wells)

(5) H. S. YODER: Influence of volume change on magma production and extrusion (15 minutes)

(6) F. R. BOYD and GEORGE KENNEDY: Some experiments and calculations relating to the origin of welded tuffs (15 minutes) (to be presented by Mr. Kennedy)

(7) E. C. CALLAGHAN: Studies of volcanic glass in New Mexico (10 minutes)

(8) J. VERHOOGEN: The temperature at the boundary of the Earth's core (10 minutes)

(9) C. L. JONES, P. H. DODD, and R. M. GARRELS: Crystallization and rock textures (15 minutes) (to be presented by Mr. Garrels)

(10) E. WILLIAM HEINRICH: Structural features of some Fennoscandian pegmatites (10 minutes)

(11) P. M. HURLEY: Heat flow and chemical segregation of the mantle (10 minutes)

SECTION OF HYDROLOGY

Monday, April 30, 1951, 09h 00m, Room 1 (Auditorium, National Academy of Sciences)

Business Session

Reports of officers and other business

Scientific Sessions

(R1) W. W. HASTINGS: Report of the Research Committee on Chemistry of Natural Waters (10 minutes)

(R2) J. W. JOHNSON: Report of the Research Committee on Dynamics of Streams (by title)

(1) HERMANN von SCHELLING: Most frequent particle paths on the unit sphere (by title)

(2) F. E. SWAIN: Determination of flows in interconnected estuarine channels produced by the combined effects of tidal fluctuations and gravity flows (20 minutes)

(3) A. CRAYA: Evaluation of the critical regime in stratified flow (20 minutes)

(R3) L. L. HARROLD: Report of the Research Committee on Infiltration (10 minutes)

(4) M. S. HANTUSH and C. E. JACOB: Non-steady Green's function for an infinite strip of a leaky aquifer (15 minutes) (to be presented by Mr. Jacob)

(R4) W. C. ACKERMANN: Report of the Research Committee on Precipitation (10 minutes)

(5) D. E. DONLEY: Maximum daily temperature as indicator of temperature excess (20 minutes)

(6) F. A. HUFF and G. E. STOUT: A study of thunderstorm rainfall on small watersheds (20 minutes) (to be presented by Mr. Stout)

(7) I. P. KRICK: Some evaluations of sustained cloud seeding operations (20 minutes)

(8) E. J. GUMBEL: The circular normal distribution (20 minutes)

Tuesday, May 1, 1951, 09h 00m, Room 3 (Auditorium, General Services Building)

(R5) W. U. GARSTKA: Report of the Research Committee on Snow (10 minutes)

(9) A. R. CROFT: Rainstorm runoff over snow (by title)

(10) R. F. BLACK: Some techniques and equipment for the study of ground ice and permafrost (20 minutes)

(11) R. A. WORK, M. G. NELSON, and H. G. WILM: Use of snow surveys in planning regulation of the Columbia River peaks (20 minutes) (to be presented by Mr. Wilm)

(R6) W. O. FIELD: Report of the Research Committee on Glaciers (10 minutes)

(12) J. E. FISHER: Control of cycles of glaciation by variations in the flow of the internal heat of the Earth and possible causes of such variations (20 minutes)

(13) W. O. FIELD: Recent glacier variations in Glacier Bay, Alaska (20 minutes)

(R7) H. V. PETERSON: Report of the Research Committee on Land Erosion (10 minutes)

(14) M. L. ALBERTSON: Turbulence flume to measure bed load (20 minutes)

(R8) G. B. BODMAN: Report of the Research Committee on Physics of Soil Moisture (20 minutes)

(15) C. H. M. van BAVEL and A. W. WALTNER: An electrical analogue for the study of diffusion processes with internal gains or losses (20 minutes) (to be presented by Mr. van Bavel)

Tuesday, May 1, 1951, 14h 00m, Room 1 (Auditorium, National Academy of Sciences)

(R9) C. F. IZZARD: Report of the Research Committee on Runoff (10 minutes)
(R10) A. R. CROFT: Report of the Research Committee on Evaporation and Transpiration (10 minutes)
(R11) J. L. HOUGH: Report of the Research Committee on Lakes (10 minutes)
(16) B. C. GOODELL: A method of comparing the flow from a pair of experimental watersheds (20 minutes)
(17) A. B. TAYLOR and H. E. SCHWARZ: Unit hydrograph lag and peak flow related to basin characteristics (by title)
(R12) J. F. POLAND: Report of the Research Committee on Ground Water (10 minutes)

Symposium on Phreatophytes

(18) H. F. BLANEY: Determining evapotranspiration by phreatophytes from climatological data (15 minutes)
(19) J. T. KOOGLER: Phreatophyte control on irrigation projects in New Mexico (10 minutes) (to be read by H. S. Riesbol)
(20) S. F. TURNER and H. E. SKIBITZKE: Use of water by phreatophytes in 2000-foot channel between Granite Reef and Gillespie Dams, Maricopa County, Arizona (15 minutes) (to be presented by Mr. Turner)
(21) T. W. ROBINSON: Phreatophytes and their relation to water in western United States (20 minutes)
(22) S. R. CRAMER: Activities of the South Pacific Division, Corps of Engineers, in eradication and control of phreatophytes (15 minutes) (to be read by S. F. Turner)
(23) C. W. BOWSER: Water conservation through elimination of undesirable phreatophyte growth (10 minutes) (to be read by H. S. Riesbol)

SECTION OF TECTONOPHYSICS

Wednesday, May 2, 1951, 09h 00m, Room 2 (Lecture Room, National Academy of Sciences)

Business Session

Reports of committees and other business

Scientific Session

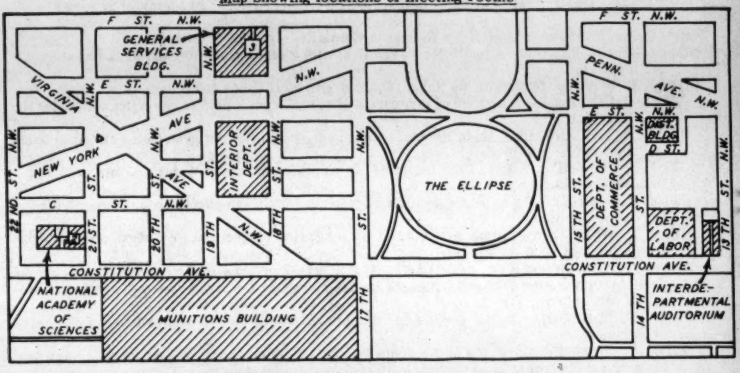
(1) H. J. WERNER: A preliminary report on the structure of the Vesuvius Quadrangle, central Blue Ridge (15 minutes)
(2) LEO A. HERRMANN: The structural geology and petrology of the Stone Mountain-Lithonia District, Georgia (15 minutes)
(3) ERNST CLOOS: Structure of the area between Washington, D. C., and Harpers Ferry, West Virginia (20 minutes)
(4) JUDSON L. ANDERSON: Metamorphism in Howard and Montgomery Counties, Maryland (20 minutes)
(5) A. NADAI: Problems of the rock shell of the Earth (25 minutes)
(6) J. TUZO WILSON: A possible explanation of some geophysical and geological observations according to the contraction hypothesis (25 minutes)
(7) W. S. JARDETSKY: On the problem of Atlantis (15 minutes)
(8) JOHN W. GRAHAM and O. W. TORRESON: Contrasting magnetizations of flat-lying and folded Paleozoic sediments (15 minutes)

NOTES

Room Reservations--Make hotel or room reservations directly with the hotel of your choice as soon as possible (see December, 1950 issue, p. 954, for word concerning hotels at which block bookings have been made). Bear in mind that advance bookings on which deposits have not been made are cancelled two weeks in advance, and thus, during this interval, chances of making a reservation may be quite good. Our meeting is scheduled again for the same week as the convention of the United States Chamber of Commerce. In previous years we have met at the same time as the convention of the DAR, but at no time, to our knowledge, has it not been possible to find quarters. Even though no advance reservation has been made, it has been possible to arrange for quarters after arrival in Washington through the Housing Bureau of the Greater National Capital Committee (204 Evening Star Building, Washington 4, D. C., telephone REpublic 2600); but they may find it necessary to direct you to a tourist home.

Registration--All members and guests attending any session are requested to complete cards of registration at the Main Registration Desk at the entrance to the Building of the National Research

Map showing locations of meeting rooms



Key to room numbers

1--Auditorium, National Academy of Sciences - National Research Council Building
2--Lecture Room, National Academy of Sciences - National Research Council Building
3--Auditorium, General Services (Old Interior) Building

Council - National Academy of Sciences, where Receptionists will be available to supply information regarding meetings, membership, telephone and mailing facilities, and other local matters. An auxiliary Registration Desk will also be maintained at the entrance to Room 3 (Auditorium, General Services Building). There is no charge for registration.

Discussion--Within the available time, opportunity will be given for discussion from the floor following the oral presentation of a paper. Discussors are urged to prepare their comments for consideration for publication with the paper.

Resolutions--Chairman Mary C. Rabbitt of the Union's Committee on Resolutions, desires to have this Committee fully advised by 15h 00m, Tuesday, May 1, 1951, of any resolutions to be submitted in order that this Committee may have opportunity to prepare them in final form for presentation at the Business Session of the Union on Wednesday afternoon, May 2, 1951. Each resolution presented to the Committee should include (a) names of original submitters, (b) whether presented to a Section, and action taken, and (c) whether action is desired in the Business Session or whether the resolution is to be regarded as being only for a particular Section or as one to be more effective as a general resolution of the whole Union. In addition to the Union's Committee on Resolutions, each Section has such a Committee. Section officers can supply information concerning these.

Conference Room--The Reading Room (west end of the first floor behind the Library) of the National Academy of Sciences is available by arrangement for conferences. See J. Putnam Marble, Chairman of the Committee on Meetings, for assignment.

Lounge--The Board Room (behind the Lecture Room), the Library (opposite the Lecture Room), and the Reading Room (behind the Library) (when not in use for conferences and committee meetings) of the National Academy of Sciences are available for the use of members to meet friends and to hold informal conferences. Those held in the Library should pay deference to the usual library regulations with regard to quietude.

Standard of time--As this program goes to press, there is uncertainty as to whether the District of Columbia will be on Eastern Standard or Eastern Daylight Saving Time at the time of the meeting. Judging from the past years, however, it is likely that Daylight Saving will be adopted.

ABSTRACTS OF PAPERS

SYMPOSIUM ON THE MEASUREMENT OF GEOLOGIC TIME

(2) R. C. Moore (University of Kansas, Lawrence, Kansas) Stratigraphic Viewpoints in Measurement--The stratigrapher's work is aimed at (1) achieving the most practically useful objective classification of stratified rock units, (2) determining their age relationships, and (3) deriving from them a reliable geologic time scale. Excepting geophysical and geochemical evidence for fixation of scattered time bench marks, all time-gaging criteria at his command lack reliable means for conversion into any precisely specified time units. Although stratigraphic approach to time measurement is qualitative and relative, rather than directly and reliably quantitative, it is essential in interpreting and coordinating geophysical data on geologic time. Problems of classifying and utilizing these data, obtained by various techniques, are discussed. Conclusion is stated that as yet very few geologic time determinations are useful in calibrating divisions of the time scale which correspond to named systems, series, and stages.

(3) Edward McCrady (U. S. Atomic Energy, Oak Ridge, Tenn.) The Use of Lead Isotopic Ratios in Age Determinations--Since the publication of Nier's determinations of the isotopic ratios in lead ores of different stratigraphic horizons from Pre-Cambrian to Tertiary, four more or less independent efforts have been made to use these data as a basis for calculating the age of the Earth. In addition to the fact that more data are required to establish statistical validity for any of these methods, they all share a common fault of assuming that we already know with reasonable accuracy the age in years of one or more of these ores independently of any radiological evidence. After reviewing the theoretical background and calculating the effect of recent re-evaluation of the decay constants, it is the purpose of this paper to propose a new approach using rock lead, which should make it possible to measure time backward from now, instead of from the assumed time of extraction of any given ore from source rocks or magmas.

(4) F. H. H. Roberts, Jr. (Smithsonian Institution, Washington, D. C.) Carbon 14 Dates and Archeology--The development of a method based on the half-life of radiocarbon whereby the age of certain objects can be determined through a series of laboratory tests has provided the archeologist with a time scale which is a valuable aid in placing various types of remains in their proper chronological position. Although the standard deviations in some cases are relatively large, the approximate age indicated is very helpful. Thus far it has been found that the method works best on samples 1,000 and more years old.

In most cases the Carbon 14 dates have substantiated the conclusions of the archeologists with respect to the sequence of different cultures, but in a few instances the results have been quite contrary to accepted beliefs. Consequently considerable revision may be necessary in certain current ideas unless it is demonstrated that for some reason or other the dates obtained are in error. Greatest interest at this time probably relates to the dates for the so-called "Early Man" in the New World. In a number of cases there is a close correlation between the age as determined by Carbon 14 and that estimated by the geologists, but in others there is considerable discrepancy. A satisfactory explanation for the differences has still to be made, although it would appear that some revision is indicated for the geologic concept of the time involved.

(5) P. M. Hurley (Massachusetts Institute of Technology, Cambridge, Mass.) Helium Retentivity versus Alpha Activity in Zircon and Sphene--The question of helium leakage from sound crystal structures of common rock minerals has not been resolved. As part of a general study of the measurement of the age of common igneous rocks, an investigation was made of the helium retentivity of zircon and sphene. These minerals are common radioactive accessories in igneous rocks and it was possible that the local concentrations of alpha activity in these minerals might damage the crystal structures sufficiently to permit the escape of helium.

Helium age ratios on a number of specimens of zircon and sphene show a progressive loss of helium with increase of alpha ionization and helium "pressure." The measurements show a range from essentially complete retentivity for samples with less than about 2.5×10^{14} alpha disintegrations per mg to almost total loss of helium from samples having suffered $7.0 \times 10^{15} \alpha$/mg. Measurements of the level of activity of accessory zircons in granites show that helium losses in the vicinity of these active centers may be as high as 90 pct, and that this effect may account at least in large part for the low helium ratios in granites as a whole.

(6) J. L. Kulp (Lamont Geological Laboratory, Columbia University, Palisades, N. Y.) Progress Report on Age Work at Lamont Geological Observatory--Recent results on age and radioactivity studies of deep-sea cores are presented. Developments in the technique of measuring natural radio carbon and its application to problems in geology are discussed.

(7) L. H. Ahrens (Massachusetts Institute of Technology, Cambridge, Mass.) Some Newer Developments of the Strontium Method Applied to Lepidolite and Biotite, and the Feasibility of a Calcium Method--An improvement in the intensity ratio method (I Sr line/I Rb line) is discussed as well as quantitative spectrochemical methods for determining rubidium and strontium in lepidolite. Several recent lepidolite age determinations are given.

The strontium method may be applied to rock biotite. For this purpose, quantitative spectrochemical methods have been developed for determining rubidium and strontium in biotite. The chemical concentration of strontium from biotite is facilitated by the presence of significant quantities of calcium in this mineral. A mass spectrographic analysis may be made of strontium in an Sr-Ca enrichment fraction. One age determination is given.

The probability of developing a calcium method is high. After considering several aspects of a calcium method, one is led to conclude that such a method would be restricted in scope. Ancient lepidolite is probably the most suitable mineral, perhaps the only one, which could be used for age determinations.

SECTION OF GEODESY

(1) Warren D. Forrester (Geodetic Survey of Canada, Ottawa, Canada) A Discussion of the Accuracy Required in Astronomic Determinations for Laplace Azimuth Control--The need of increasing the number of observations for azimuth as one approaches higher latitudes is discussed, and frequent reference is made to differences of opinion existing between two members of the Geographical Service of Norway in regard to the value of Laplace azimuths in the adjustment of triangulation observed in the Far North. A tabulation of the ratio of work required at any latitude, relative to that at 45° latitude, is given for both azimuth and longitude observations in order to secure comparable accuracy.

(3) Julius L. Speert (U. S. Geological Survey, Washington, D. C.) Radar Altimetry Operations of the U. S. Geological Survey in 1950--This paper describes the methods employed in obtaining ground elevations for topographic mapping by the use of an airborne radar altimeter and related equipment. The 1950 program of the Geological Survey in Alaska is described and some of the results obtained are presented and discussed.

(4) Manuel Medina (Dirección de Geografía y Meteorología, Oficina de Geografía, Tacubaya, Mexico) The Geodetic Work in Mexico from May 1950 to April 1951--Continuing substantial progress has been made during the last year on triangulation, geodetic astronomy, and precise leveling in Mexico. In addition, the seven 24-m invar wires of the Bureau were standardized with the four-meter invar bar. A new gravimetry base station has been established in the pier base of the Bureau with invar pendulums, preparatory to new circuits of gravimetric determinations.

(5) W. Heiskanen (Director of the Finnish Geodetic Institute, and Professor, Institute of Geodesy, Photogrammetry, and Cartography, Ohio State University, Columbus, Ohio) Recent Progress in Geophysical Geodesy--Since gravity measurements were extended to the oceans, and since new, accurate, and rapid gravimeters were devised, the achievements in geophysical geodesy have become more and more striking. Geophysical geodesy, that is, the gravity anomalies and the deflections of the vertical, can give us the accurate shape of the geoid. Together with the astronomical observations, the gravity survey enables us to compute the absolute deflections of the vertical at any desired point in the world. The accuracy is so high that the maps 1:250,000 and, in many large regions of the world, even the maps 1:100,000 can be controlled astronomic-gravimetrically. Also the dimensions of the used reference ellipsoid can be corrected, and the general World Geodetic System established. The structure of the Earth can be studied as well.

(6) G. D. Garland (Department of Physics, University of Toronto, Toronto, Canada) Gravity Measurements in the Maritime Provinces of Canada--During the summer of 1950, over 300 new gravity stations were established by the Dominion Observatory in Nova Scotia, New Brunswick, and Prince Edward Island. The Bouguer anomalies computed from these observations are discussed, and a correlation with the major geological structures is indicated. In particular, the large negative anomalies known to exist over Devonian granite batholiths are examined, in order to obtain information on the depth extent of these features. Similarly, negative anomalies observed over sedimentary basins are interpreted in terms of the possible thickness of the low density sediments. A finding of particular interest is the apparent extension of the Caledonian Mountains of New Brunswick beneath the Carboniferous sediments of Prince Edward Island.

(7) J. Lamar Worzel and Maurice Ewing (Lamont Geological Laboratory, Columbia University, Palisades, N. Y.) Gravity Measurements at Sea, 1950--The long-range program of gravity mea-

surements at sea has been continued on board submarines of the U. S. Navy. Improvements in the Vening Meinesz apparatus have included an alternating-current light source, and two fiduciary markers to place reference lines on the records. During 1950 gravity observations were made as follows: On USS Sea Dog between Hawaii, Japan, Philippine Islands, Guam, and Hawaii; on USS Bergall between Hawaii, Panama, Windward Passage, Crooked Island Passage, and New London. The techniques have been developed and tested to make all of the computations necessary to reduce the gravity observations on IBM machines.

(8) G. P. Woollard (University of Wisconsin, Madison, Wis.) The Development of the World Gravimeter Network to Date--Since the establishment of the first world-wide gravimeter measurements in 1948 as a loop around the world based on Washington, D. C., continental networks of stations have been established in South America, Africa, and Australia. In carrying out these later measurements, it has been possible to reoccupy several of the earlier bases occupied and to evaluate the accuracy of the observations. In at least two instances reading errors of one scale division on the original observations were discovered which fortuitously did not affect the network as a whole. It is planned to repeat this year the world-girdling traverse as a series of closed loops, and build up during the next three-year period the continental networks in order to facilitate tying in national and privately completed surveys in various parts of the world. Measurements are also being made at the various port stations of the submarine gravity surveys so as to tie the two basic networks of stations together. This program is being supported by the Office of Naval Research.

(9) Howard S. Rappleye (U. S. Coast and Geodetic Survey, Washington, D. C.) Precision Leveling at the White House--This paper deals with the planning and execution of a precision-leveling program being carried on during the reconstruction of the Executive Mansion in Washington, D. C. Unusual accuracy requirements and unusual working conditions were responsible for many departures from established practice in precision leveling. Field methods, instrumental equipment, accuracy of leveling, and observed behavior of bench marks are discussed. Special emphasis is on the unusual features of the work rather than the description of just one more leveling project.

SECTION OF SEISMOLOGY

(1) William L. Donn (Department of Geology, Brooklyn College, Brooklyn, N. Y.) Observations Bearing on the Origin and Propagation of Microseisms--Nearly all of the microseism storms generated by fronts, extratropical cyclones, and hurricanes in the western North Atlantic during the fall and winter seasons of 1948-1949 and 1949-1950 have been studied, together with some storms that occurred during the fall-winter of 1950-1951. Seismograms from a large number of stations along the eastern and Gulf coasts of United States and the West Indies and Bermuda were examined for each storm. Each of the microseism storms have been correlated with a particular marine atmospheric disturbance. The period of the microseisms generated appears to be a function of the depth of water in the generating area, and the regularity of the microseism is a function of the uniformity of depth in the generating area. The effect of distance between the generating area and the station seems to be a selective one owing to more rapid decay of short-period microseisms. As a consequence of the above empirical generalization the position and nature of marine disturbance can often be estimated from the nature of the recorded microseisms.

All the evidence on origin tends to negate ocean swell, standing waves produced by interference of ocean swell, and surf as mechanisms producing the observed microseisms. The study suggests atmospheric pulsations resulting from turbulence, or instability to be at the root of microseism origin. Anomalies of propagation of hurricane microseisms suggest the existence of a zone or surfaces of discontinuity along at least a portion of the outer margin of the East-Coast continental shelf.

(2) Daniel J. O'Halloran (U. S. Coast and Geodetic Survey, Washington, D. C.) A Microseismic Study of Cold-Front Passage over Inland Bodies of Water--A cold front (Cpk) passed over the Great Lakes region January 3-4, 1950, and reached the Atlantic Ocean January 7, 1950. The progress of the eastward moving cold air was correlated with microseisms recorded on seismographs at Chicago, Cleveland, Buffalo, and Washington, D. C. There seems to be definite indications that the wind associated with strong cold fronts is responsible for long T microseisms recorded at stations in the immediate vicinity of a large body of inland water. There seems to be no evidence of these long T microseisms being transmitted any great distance. The long T microseisms may result from the pounding of surf composed of groups of sinusoidal waves with smaller period oscillatory waves superimposed upon them. This would seem to indicate visual observations fail to show the longer underlying periods.

(3) Joseph Lynch (Physics Department, Fordham University, New York, N. Y.) Fordham's New Tripartite Station at Poughkeepsie, New York--A new tripartite station has been set up at Poughkeepsie on land adjoining the Roosevelt estate. The triangle is a right-angled triangle with sides 3200 ft, 2600 ft, and 2000 ft, with the short side running E-W and the 2600-ft side running N-S. Some excellent records have been obtained. Some of these are discussed. The most important is that of a storm on February 25, 1951. The source was due west of Poughkeepsie and hence on land. Being in a direct line with two of the stations 2000 ft apart, it indicates a velocity of 0.5 mi per sec for microseismic waves.

(5) Frank Press, A. P. Crary, Jack Oliver, and Samuel Katz (Lamont Geological Observatory, Palisades, N. Y., and Air Force Cambridge Research Laboratories, Cambridge, Mass.) Air-Coupled Flexural Waves in Floating Ice--Experimental studies of the propagation of elastic waves on floating ice sheets were made on the ice of Lake Superior and Lake Cayuga. Elastic waves were produced by small explosive charged detonated at various depths in the water, within the ice, and in the air. Seismic detectors consisting of a spread of geophones, a microphone, and a hydrophone recorded the resultant wave motion at varying distances. Shots in the water produced the normal sequence of dispersive flexural waves. For shots in the air the dispersive flexural waves were absent and a train of constant frequency waves was observed, beginning gradually at the approximate time $t = r/2v_a$ and culminating with the arrival of the air wave at the time $t = r/v_a$ (r is the range and v_a is the speed of sound in air). These waves were interpreted as air-coupled flexural waves. The frequency of the air-induced waves is that of flexural waves whose phase velocity equals the speed of sound in air. The generated wave train precedes the air disturbance since the group velocity of flexural waves exceeds the phase velocity, all in accordance with classical theory. The frequency of the air-coupled vibration is simply related to the ice thickness. The interpretation was supported by subsequent tests which consisted of shooting on shore and recording on the ice, shooting and recording on ice sheets of varying thickness, and recording air-coupled flexural vibrations with microphones.

(6) M. A. Tuve, H. E. Tatel, and L. H. Adams (Carnegie Institution of Washington, Washington, D. C.) Coherent Explosion Wave Patterns at 100 Kilometers--Last year we established that any two seismometers 100 km from a shot, spaced only tens of meters apart, yielded records appreciably different. This served to corroborate our earlier observation that much of the observed ground motion was due to scattered energy. More complex arrangements were employed to compare records, for example, of seismometers spaced along a line one km in length. The advantages of these arrangements are that (1) any truly coherent reflected or refracted signals can be observed within the large background of scattered radiation, and (2) the signals could be recognized by the systematic ground motion of a small region (rather than at a point). The culmination of these trials is two sets of apparatus similar to that used in geophysical prospecting. Forty-eight seismometers are arranged in a line 75 ft apart and successive pairs are paralleled and recorded on a multichannel 24-trace oscillograph. The line may be arranged in an L or T depending upon circumstances.

Radiation from the Mohorovicic discontinuity has now been observed in a region at 100 km where it had previously escaped detection. The pattern of the multiple seismogram is complex and, while not completely understood, is perhaps an indication of buried topographic features at the discontinuity. Mixing of the outputs of successive amplifiers in an orderly fashion enhances the apparent signal-to-noise ratio. True coherent radiation is indeed more easily recognized by the distinctive patterns on the multiple seismogram and their physical reality thereby more readily established than with the single instrument method.

A shear wave has been recognized at 100 km, for the first time, and provisionally designated as S33S.

(7) H. E. Tatel, M. A. Tuve, and L. H. Adams (Carnegie Institution of Washington, Washington, D. C.) Crustal Structures Indicated by Explosion Wave Patterns--We have again analyzed all of our seismic data with severe restrictions on physical reality. The necessity for these strict criteria arises on two accounts: (1) the realization that most of the ground motion recorded on a seismogram is due to scattering of various kinds, and (2), as pointed out particularly by Slichter, that late arrivals must in general be recognized in order to establish the reality of a discontinuity. The results of the analysis are that the Mohorovicic discontinuity is observed in some regions and evidently not in others; and this is the only discontinuity observed in point-by-point observations (six or eight single stations) in the regions we have explored. Discontinuity is here used in the sense dictated by the limitations of the seismic method requiring certain minimum velocity contrasts. Sporadic observations of breaks in the travel-time curves derived from observations from shots at a single locality are attributed to unordered structures within the crust; this is perhaps the most general crustal characteristic. Comparison of two separate localities (Maryland and Tennessee) shows that the greater measured seismic depth of the Mohorovicic discontinuity in Tennessee is accompanied by a greater negative Bouger gravity anomaly.

(8) M. B. Dobrin, R. F. Simon, and P. L. Lawrence (Field Research Laboratories, Magnolia Petroleum Co., Dallas, Texas) Rayleigh Waves from Small Explosions--As part of a program to study ground disturbances that interfere with seismic prospecting, an experimental seismic crew of the Magnolia Petroleum Co. has been investigating Rayleigh waves from shot-hole explosions at distances up to about 3000 ft. Waves have been recorded by vertical and horizontal geophones through a system giving flat response between 5 - 200 cps. The geophones have been disposed along surface profiles with separations that are short compared to Rayleigh wave lengths and also at various depths up to 100 ft in boreholes. Rayleigh waves from air explosions have also been recorded.

Sample arrays of records are presented on which individual waves from hole and air shots can be followed for horizontal distances up to about ten wave lengths. Dispersion characteristics observed on the records are plotted in a form permitting comparison with theoretical dispersion curves for various kinds of surface layering. Effects of varying the depth of the explosion are observed and compared with theoretical predictions. Particle motion trajectories are plotted both at the surface and at various depths. Results all show as good agreement with classical theory as can be expected in view of the simplifying assumptions which must be made deriving this theory. Constant-frequency wave trains were observed immediately after the air-wave arrival on the records made from single air explosions eight feet above the ground These are shown to be waves of the type predicted by the Press-Ewing theory of surface wave coupling to the atmosphere.

(9) Peter Dehlinger (Battelle Memorial Institute, Columbus 1, Ohio) Shear-Wave Vibrational Directions and Related Fault Movements in Southern California Earthquakes--Vibrational directions of direct shear waves from a number of small local earthquakes in Southern California, recorded at Pasadena and Riverside, have been determined and related to corresponding faulting at the source. A relationship between the direction of small fault displacements and vibrational directions of resultant P, SV, and SH waves near the source is proposed, from which the vibration directions of direct SV and SH waves from various fault types can be adduced. Observations of initial shear-wave motions from this investigation indicate a general consistency of direction of SH components, but usually less consistent direction of SV components. Values of the ratio of initial amplitudes of SV/SH are consistent within a few regions, but generally vary widely. The data indicate that the direct SH waves are probably polarized. Polarization of the SV waves is suggested, but not clearly indicated by the data. From the SH wave data, it appears that the horizontal components of present-day faulting usually take place in the same direction within local regions in Southern California. Directions of vertical components of such faulting appear to vary. A comparison of the observed SH and SV first motions is made with the theoretical shear motions and with Gutenberg's observations of impulses of compressional waves. A resultant fault pattern consistent with the seismic data and the regional surface geology is postulated which involves primarily northwesterly trending, right-handed transcurrent faults in some regions of Southern California, east-west trending reverse or thrust faults in others, and a coexistence of the two in a few localities. A somewhat simplified crustal stress distribution, consistent with the data, has been postulated.

(10) P. G. Gane (Department of Geodesy and Geophysics, University of Cambridge, Cambridge, England) Rockburst Seismology in South Africa--The rockbursts of the Witwatersrand occur at a rate of up to ten per day in a mining area some 60 mi long by several miles wide. Partly because there are extensive old workings in the area, and because the underground population is small at certain times of the day, there is rarely satisfactory evidence from the mine administrations of the local situation of these shocks, which therefore have to be located by seismic methods. For this purpose, a system of radio links has been applied which allows six distributed seismometers to record at one place. In addition, a high recording speed is obtained by storing these records there for a few seconds on a magnetic tape unit which plays them back to a recorder which has been triggered by local seismometric equipment. By these means, relative arrival times are measurable to 0.01 second. The seismograms show a strong S phase which is nearly as valuable as the P phase.

The triggering apparatus has also been arranged to send a trigger-signal, with superimposed time-marks, by radio to field apparatus operated by a camping party. It is usual to record two or more tremors a day at any distance up to 700 km from their origin.

Several hundred seismograms have been obtained of these shocks at distances mostly within 500 km. A recent analysis showed P and S velocities of 6.09 and 3.68 km/sec within 170 km, and 8.27 and 4.83 km/sec beyond that distance. Except within 20 km of the epicentre, where there is known to be a great depth of sedimentary rock, there is no indication of a velocity less than 6 km/sec, but the country to which these figures refer had numerous granite outcrops and was specially chosen to be as representative of the basement as possible. The total depth of the crustal layers is estimated to be 37 ± 3 km. There is certainly a variation of velocity with depth, but the observations do not as yet permit of its specification with confidence. It is believed that the crustal

conformation is by no means as simple as is often supposed, and that any interpretation of travel-time data more accurate than 0.5 second must take account of local conditions at the sites both of the shock and of the field seismographs.

SECTION OF METEOROLOGY

(1) William C. Spreen (Air Weather Service, Washington, D. C.) and Nicholas Manos (Public Health Service, Washington, D. C.) Probabilities from Limited Weather Data--A brief description and discussion of several problems in applied climatology. The probability of occurrence and the frequency distributions of the effects of various weather elements are calculated from limited information by means of statistical analysis.

(2) George L. Arnold (Air Weather Service, Washington, D. C.) Relation Between Cloud Cover and Cloud Height--An applied climatological problem relating frequency of various cloud covers to frequencies of various cloud heights in an attempt to provide a method of estimating frequencies of cloud heights in areas where only frequency of various covers are available. This discussion has been limited to the winter season in the eastern United States.

(3) Walter Hitschfeld (Department of Physics, McGill University, Montreal, Canada) Free Fall of Drops through Air--Terminal-velocity data of water drops are used for the quantitative description of the accelerated motion of water drops falling freely from rest. The method, based on the principle of aerodynamic similarity, is valid for water drops of radius 1.6 mm or less. Using, as an example, the Schmidt relation for terminal velocity, general expressions are obtained for the time of fall and the distance fallen as functions of the velocity of fall attained. Numerical results calculated for drop radii of 0.63, 1.00, and 1.50 mm agree well with the measurements of Laws.

(4) Patricia A. Langwell (Department of Meteorology, New York University, New York, N. Y.) The Onset of Rain from Cumulus--A kinematic study of the growth of a cumulus cloud leads to criteria for judging whether rain will fall. A forecast is made for the area of the cloud from which rain will first fall, with relation to the instability and the wind field.

(5) L. L. Weiss (U. S. Weather Bureau, Washington, D. C.) Moisture Accumulation Rates in Thunderstorm Cells--Limits on the duration and amount of moisture accumulation are estimated from computations based on the empirical results of Byers and Braham applied to idealized cells involving assumptions of radial symmetry, zero divergence of specific momentum, U. S. standard atmospheric temperature-height curve, no horizontal density difference, saturation, and a steady-state flow pattern applied instantaneously. Stationary cells of two sizes in a general area of no wind and another case of a cell in a general velocity field of ten miles per hour relative to the cell are considered. Maximum rates of about one inch per hour are found for all three cells. The duration is about one hour for the stationary cell of three-mile radius, five hours for the stationary one of five-mile radius, and 30 minutes for the moving cell.

(6) W. H. Wyatt (Air Weather Service, Washington, D. C.) Daily Fluctuation of the Aretic Inversion--Time sections were used to study the daily fluctuation of the Arctic Inversion at three selected stations (Point Barrow, Churchill, and Norman Wells) during January and February 1949. The diurnal fluctuation was eliminated as much as possible by plotting only the early morning soundings. Since altitude information was not available at the time, the time sections used pressure in millibars as the ordinate. These time sections indicated that the height and magnitude of the Arctic Inversion varied considerably from day to day. The fluctuation was attributed to several factors such as radiation, advection of warm and cold air, and dynamic meteorological processes.

(7) Ronald L. Ives (Physics Department, Cornell Aeronautical Laboratory, Buffalo, N. Y.) Recurrent Mirages at Puerto Peñasco, Sonora--Mirage behavior at Puerto Peñasco, on the Sonoran shore of the Gulf of California, is not only systematic, but is fully compatible with conditions of atmospheric refraction common in that arid area adjacent to a tropical sea. Images of mountains in Baja California, normally hidden below the visual horizon, are regularly loomed into visibility as the lapse rate in the lower layers of the atmosphere increases, and sink again below the horizon with the onset of nocturnal inversions. False sea horizons, due to refraction, are a standard mid-day condition, as are inferior mirages over adjacent land areas. Air stratification is normally accompanied by "paper doll" duplications of distant images; fata morgana is a common occurrence when cold-air drainages from high mountains reach the warm waters of the Gulf of California. Photographic differentiation between mirage lakes and actual bodies of water is sometimes possible by use of deep red filters.

(8) Philip F. Clapp (Extended Forecast Section, U. S. Weather Bureau, Washington, D. C.) Kinematic Vortex Theory Applied to the Motion of Anomalies of the General Circulation--The kinematic theory of vortex interaction, as portrayed by the well-known von Kármán vortex street, is applied to the problem of predicting the motion of selected large-scale centers of action. Anticyclonic or cyclonic centers of action are defined as regions of maximum positive or negative departure from normal of 700 mb height taken from five-day and monthly mean charts. Preliminary results indicate some degree of skill. Perhaps more important, it may be possible to foretell when a given forecast will succeed.

(9) Seymour L. Hess (Florida State University, Tallahassee, Fla.) The Effect of the General Circulation on the Latitudinal and Temporal Distribution of Temperature--The effect of the general circulation upon the distribution of temperature is studied on the assumption that the latitudinal transfer of heat is effected mainly by large-scale, turbulent, horizontal mixing, characterizable by a single exchange coefficient. The resultant diffusion equation for the temperature, together with suitable time-dependent boundary conditions near the pole and the equator, yield a theoretical variation of temperature with latitude and time. The main characteristic of this solution is its prediction that the times of maximum and minimum temperature must occur later and later the lower the latitude. There is some observational evidence that this actually occurs.

(10) Thomas A. Gleeson (Department of Meteorology, Florida State University, Tallahassee, Fla.) On the Theory of Cross-Valley Winds Arising from Differential Heating of the Slopes--By means of equations of horizontal motion and astronomical considerations, expressions are derived for a cross-valley wind caused by differential solar heating on opposite slopes. Friction, inertia, the Coriolis force, the time of the day and year, the latitude and orientation of the valley, and the inclinations of the slopes are independent variables in these expressions. Absolute wind speeds cannot be determined by this theory, but directions and variations in speed may be studied. Several examples illustrating effects of the independent variables on the cross-valley wind are discussed, and a comparison of observation with theory is made for a specific valley.

(11) Joanne Starr Malkus and Melvin E. Stern (Illinois Institute of Technology, Chicago, Ill.) Airflow over a Heated Island--The effect upon a stable atmosphere of a heat source which is a specified function of the coordinates is investigated theoretically. A two-dimensional problem is chosen, with the x-coordinate in the direction of the constant undisturbed wind, v, and the z-direction is vertical. The heat source, a finite-width pulse in x, has maximum amplitude at the ground ($z = 0$) and decays with height. A steady state, in which the heat supplied by the source is continuously carried away downstream is assumed, and the equations of motion are linearized by the method of perturbations. By Fourier analysis of the pulse function, the perturbation equations are made separable, and solutions for the disturbed vertical and horizontal wind fields and temperature field are obtained. It is shown that "lee waves," that is, downstream oscillations in the vertical motion field, do not occur unless the stability or undisturbed wind undergo a change in the vertical. The results of the theoretical analysis are to be compared with observations made by the Woods Hole Oceanographic Institution over Nantucket Island, a flat, sandy strip about five km in width. The work discussed in this paper was carried on under Contract Nonr-174(00) with the Office of Naval Research.

(12) Lewis D. Kaplan (U. S. Weather Bureau, c/o Department of Meteorology, University of Chicago, Chicago, Ill.) The Pressure Dependence of Radiative Heat Transfer--Recent experimental evidence seems to verify direct pressure broadening. This simplifies the expression for the fractional transmission. Using Elsasser's absorption coefficient, $k(\nu)$, for lines of equal intensity and equal spacing, one obtains

$$\tau = (1/\pi)\int_0^{\pi} [(\cosh \beta_2 - \cos s)/(\cosh \beta_1 - \cos s)]^K \, ds$$

where the symbols are those used by Elsasser in 1942 and K = (fraction by volume) $\times Sp_s/2\pi a_s \rho_s g$. The series expansion for this integral is given. Stratospheric heating and cooling rates caused by carbon dioxide are calculated. The effects of water vapor, ozone, and the variation of absorption coefficients with temperature are discussed qualitatively. It is found that carbon dioxide cannot be neglected in heat-transfer calculations.

(13) Wm. S. Wilson, W. G. Guenther, Robert D. Lowrey, and Joseph C. Cain (Geophysical Institute, University of Alaska, College, Alaska) Concentration of Surface Ozone at College, Alaska, for the Year 1950--The daily average concentration of ozone in the atmosphere at the surface of College, Alaska, was determined during the year 1950 by the absorption of ozone in a solution of potassium iodide in standard arsenite. The results are plotted with pressure and temperature data. The average value for this period is 9.8 milligrams of ozone per hundred cubic meters of dry air (STP). The research reported in this paper was carried out under Contract W28-099 ac-445 with the Geophysical Research Directorate of the Air Force Cambridge Research Laboratories.

SECTION OF TERRESTRIAL MAGNETISM AND ELECTRICITY

(1) Ralph J. Havens (Naval Research Laboratory, Washington, D. C.) Atmospheric Pressure and Density to 160 Kilometers--A program of atmospheric pressure and density measurements with rockets has given values up to about 160 km above sea level. Ambient pressures were measured up to 120 km on nine rockets fired at White Sands, New Mexico, and up to 70 km on one rocket fired at the equator. Densities were measured up to about 160 km on two rockets. At 157 km the density was $2.0 \pm 0.5 \times 10^{-12}$ gm/cm^3. Temperatures, calculated from pressure and density data, rose to about 280°K at 50 km, dropped to less than 200°K at 75 km and increased above 80 km.

(2) T. R. Burnight (Naval Research Laboratory, Washington, D. C.) Soft X-ray Intensities Measured in the Upper Atmosphere--Photographic film behind thin, optically opaque beryllium windows was carried into the upper atmosphere on a rocket on August 5, 1948. Upon recovery and development the film was found to be darkened. The darkening was attributed to soft X-rays in the range 1.5 to 5 A. Subsequently in more than 30 rocket flights such radiation in various bands from 0 to 25 A has been studied using film, counters, and ion chambers. X-rays with wavelengths longer than 8A have been shown to be of solar origin but the source of X-radiation observed shorter than 5A has not yet been ascertained. The radiation between 8 and 11A first becomes detectable at about 92 km, rising to an intensity of 2.2×10^{-4} ergs per cm^2 per sec at altitudes about 115 km. In the 8 to 25A interval the observed intensity has varied by several orders of magnitude from flight to flight, with a maximum of 0.1 erg per cm^2 per sec observed on February 17, 1950.

(3) M. H. Johnson (Naval Research Laboratory, Washington, D. C.) Electric and Magnetic Fields about a Rocket--A rocket surface exposed to intense solar ultraviolet radiation will emit energetic photoelectrons which diffuse away from the point of production. The resulting current system and associated electric field may be important in interpreting electric or magnetic measurements from a rocket platform. Effects may also arise from the distortions in an existing current and electric field distribution produced by the rocket's presence. The possibility that the Hall component of the current system can produce an apparent change in the Earth's magnetic field comparable to that expected from a current sheet in the E-layer has been examined.

(4) M. J. Kooman, D. M. Packer, R. Scolnik, and E. O. Hulburt (Naval Research Laboratory, Washington, D. C.) Measurements of the Brightness of the Twilight Sky--In order to supplement previous measurements by this Laboratory of the brightness of the daylight and night sky, the present twilight sky data were obtained. A recording photoelectric photometer of photopic spectral sensitivity covering about eight orders of magnitude in brightness was used to measure the sky brightness in clear weather, with no moon, during twilight in the country in Maryland. Data for the entire sky on meridians at every 22 1/2 degrees from the bearing of the Sun were recorded in less than five minutes. The data were assembled in charts and tables.

(5) Renee Herman (Mouden Observatory, Paris, France) and Louis Herman (Geophysical Institute, College, Alaska) New Band Systems of Nitrogen in the Spectrum of the Aurora--Auroral spectra photographed at College, Alaska, have been compared with laboratory spectra. The structure of certain laboratory bands of nitrogen is different from that observed in the aurora as the rotational temperature seems to be lower in the aurora. The 7427 band shows a peculiar strength in both the aurora and laboratory spectra and will not fit into the $v' - v'' = 2$ sequence of the first positive bands. The work discussed in this paper was carried on under Contract AF19 (122)-431 of the Geophysical Research Directorate, Air Force Cambridge Research Laboratories.

(6) H. W. Wells (Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, D. C.) Characteristics of Local Ionospheric Disturbances--Analyses of ionospheric observations made simultaneously at three stations in a small geographical area, that is, Derwood, Maryland (near Washington, D. C.), Charlottesville, Virginia, and Morgantown, West Virginia, reveal that many events are local in nature and small in physical size compared to the distances between Derwood and Charlottesville (100 mi), or Derwood and Morgantown (150 mi). This is especially true of the cloud-like surges which cause a small but abrupt change in critical frequency of F layer followed by a characteristic downward rippling motion in the ionospheric record. A motion-picture film of high-speed ionospheric observations made to examine the fine structure of E and F regions shows the rapid development and disappearance of fully resolved ion banks at the base of F region which are directly associated with the apparent earthward travel of the cloud. The film includes some examples of horizontal motions but the clouds with vertical components only are many times more frequent. Apparent earthward velocities range between 100 and 450 km/hr with most values between 350-400 km/hr. A brief discussion is devoted to possible causes of these local ionospheric disturbances.

(7) Reynold Greenstone (Upper Atmosphere Research Section, Central Radio Propagation Laboratory, National Bureau of Standards, Washington, D. C.) Systematic Ionospheric Winds--A study of fading patterns of radio waves reflected by the ionosphere has led to the determination of horizontal drifts in the ionosphere. Equipment has been operated at 2.3 Mc at the Central Radio Propagation Laboratory since March 1949. The wind may blow from any direction over a period of time. It exhibits diurnal characteristics which change with the seasons. Wind speeds may range up to 300 m/sec, but are predominantly in the range from 50 to 100 m/sec. Marked changes in the character of the winds are associated with the transition from E to F region reflections. Good agreement is found between wind velocities observed at Washington, D. C., and those observed at Cambridge, England.

(8) Donald M. Swingle (Route 2, Box 186, Neptune, N. J.) Some Observations of the Bright-Band Radar Echo--In a series of observations over a period of 20 months, the bright-band (precipitation) echoes obtained by a 10-cm radar directed vertically exhibited striking vertical oscillations of substantial amplitude. A correlation of the height of the bright-band with the height of the freezing level at nearby radiosonde stations indicated that the bright-band level was always lower than the freezing level so determined, frequently by as much as 3000 ft.

(9) Jules Aarons (Air Force Cambridge Research Laboratories, Cambridge, Mass.) Low-Frequency Noise--Magnetic fluctuations in the frequency range one-half to 20 cycles per second have been experimentally verified. The values reported by Menzel and Salisbury and by Willis for electric field intensities are shown to be peak-disturbance values in the former case and steady-state, quiet-day values in the latter. The February 12-23, 1950 sunspot appearance, magnetic storm, and associated phenomena are studied in detail. A correlation of low-frequency noise storms with geomagnetic disturbances and ionospheric storms is noted but with time differences between the low-frequency fluctuations and the onset of magnetic storms. A diurnal effect takes place. The origin of the disturbed signal in ionospheric oscillations is suggested.

(11) Oscar Weiss (902 Mutual Building, Johannesburg, Union of South Africa) Abnormal Magnetic Polarization of Faulting in Lower Witwatersrand Shales in the Union of South Africa--Observations with vertical magnetic balance on the ground and with aerial magnetometer at various heights show that under normal, undisturbed conditions the magnetic anomalies over outcrops and sub-outcrops of the Lower Witwatersrand (LWW) shales increase the normal Earth's field. In the correct sense of physics these anomalies are negative as they are in the Southern Hemisphere, but for practical comparison of anomalies from all parts of the world the writer decided that anomalies which increase the normal Earth's field are termed positive, while anomalies which decrease the Earth's normal field are termed negative.

Over faults and over the immensely squeezed, overturned, and truncated beds of the LWW shales on the rim of the Vredefort dome, abnormal magnetization occurs. Strong negative anomalies were recorded at these places both from the air and on the ground. The aerial magnetometer established the fact that the abnormal polarization was not confined to the top zone of the shales, but penetrated to great depths. Curves of normal and abnormal anomalies are presented from different localities. It appears that major faults are accompanied by abnormal polarization, but the exact manner in which this polarization is produced remains unknown. It seems, however, that effects of squeezing, perhaps plastic flow, and faulting cause abnormal polarization. Whether the exact cause is due to rotation and stressing of the magnetite crystals, or to heat, or to all three factors being effective over very long periods of time, is not known.

In the areas investigated, two dyke systems of different ages exist. One of them give positive and the other negative anomalies. It would be interesting to know whether or not the positively magnetic dykes occupy tensional fractures, while the negatively magnetic dykes were squeezed into shear planes. Curves of magnetic anomalies are presented from observations over dykes by aerial magnetometer and the vertical magnetic balance.

(12) F. Keller, Jr., L. S. Baker, and B. C. Byrnes (U. S. Coast and Geodetic Survey, Washington, D. C.) Airborne Magnetic Operations--In a joint U. S. Air Force - U. S. Coast and Geodetic Survey project, airborne measurements of the magnetic elements D, I, H, Z, and F have been made at more than 2000 locations in the continental United States and adjacent ocean areas during the past year. The measurements are made with the Naval Ordnance Laboratory total field and direction magnetometer which, in addition to F, measures the orientation of the detector with regard to the aircraft's axes. Flights are made at an altitude of 20,000 ft, in smooth air, with the aircraft always under control of the automatic pilot, so that the pitch, roll, and yaw motions are oscillatory in nature and small in amplitude. The average orientation of the aircraft axes with regard to the Earth is determined by averaging over two-minute periods, the pitch and roll motion as indicated by a pendulum, and the true heading as indicated by relative bearings of a celestial body. The reference vertical is believed to be within 0.2° of the true vertical using this system.

Corrections are made for Coriolis force and ship's magnetism. Navigation is by all available methods and the general precision of position is of the order of ± 5 miles. Under average conditions, the elements are measured with the following estimated precision: D, ± 0.5°; I, ± 0.2°; H, ± 0.001 cgs; Z, ± 0.001 cgs; F, ± 0.001 cgs.

(13) Elliott B. Roberts (U. S. Coast and Geodetic Survey, Washington, D. C.) Punch-Card Processing of Geomagnetic Work--Routine computations in the processing of geomagnetic data have been performed successfully by IBM methods at great savings of time and personnel costs. The principal types of work so expedited have been magnetic cartography and the preparation of geomagnetic observatory results for publication. The success of the methods adopted gives reasonable hope of eliminating the serious backlog of unpublished geomagnetic data of the U. S. Coast and Geodetic Survey.

(14) Patrick L. O'Dea and H. Herbert Howe (U. S. Coast and Geodetic Survey, Washington, D. C.) Six Additional Years of Spontaneous Increase in Magnetic Moment--The spontaneous increase in magnetic moment of magnet 31LC has been the subject of two previous articles published here. The present paper, in furnishing approximately six additional years of data, reveals that the rate of increase of magnetic moment is now approaching zero, indicating the near extinction of this magnet's remarkable quality. The total increase in moment has been nearly 1.5 per cent. In contrast, a similar magnet, made in 1941 from the same type of steel, but not heat-treated at the same time, has shown a six per cent decrease in magnetic moment.

(15) David G. Knapp (U. S. Coast and Geodetic Survey, Washington, D. C.) Reversible Susceptibility and the Induction Factor Used in Geomagnetism--This paper reviews from the geomagnetic point of view the literature pertaining to characteristic curves of permanent-magnet materials and, to some extent, of softer magnetic materials, with special stress on properties of the hyperbolic demagnetization curve. Studies of published data and consideration of known properties lead to some useful relations involving reversible susceptibility κ_r, coercive force H_c, demagnetizing factor N, and the ratio H_d/H_c where H_d corresponds with the maximum energy product. Effects considered include those of scale changes in plotting the curves, reduction of B/H to I/H curves, minor hysteresis loops and magnetic stabilization, and differences in cross-sectional area and shape (for bar magnets). The paper shows that $V/\mu' = N + 1/\kappa_r$, where V is the volume of the magnet and μ' its induction factor as used in geomagnetism. It is shown that κ_r is a more suitable parameter to use for evaluating a material than is the so-called induction coefficient.

(16) R. E. Gebhardt, T. J. Hickley, and T. L. Skillman (U. S. Coast and Geodetic Survey, Washington, D. C.) A Photo-Electric Magnetograph--For the past four months the Division of Geophysics, U. S. Coast and Geodetic Survey, has been operating a photo-electric visual magnetograph. The H and D variometers are standard unifilar Survey instruments. The Z variometer is a modified Ruska. The pick-up consists of individual light sources and photo-electric tubes. The photo tubes have double cells in the single envelope (GL-920). The amplifier, built by the Radio Sonic Laboratory (USC and GS) is essentially a cathode follower, whose output feeds Esterline-Angus meters for visual recording. Comparison of records obtained with Cheltenham Eschenhagen grams are very favorable, both for stability and fidelity.

(17) Robert Warren Long (Department of Physics, University of Houston, Houston, Texas) Magnetic Observatory at the University of Houston--The variometer observatory operations were started September 25, 1950. The scale factors initially were 3.76 γ/mm for Z (vertical), 3.74 γ/mm for H (horizontal), and 1.05 '/mm for D (declination) with the following absolute data: H, 0.25810; Z, 0.45480; D, 9°04′ E. The absolute observatory was utilized for initial values but the absolute instruments are not now present. Ruska Instrument Corp. donated the variometers and recorder. The observatory is operated in part by the United States Coast and Geodetic Survey. The observatory is located at 29° 43′ N, 95° 20′ W.

(18) Edwin J. Chernosky (U. S. Naval Ordnance Laboratory, Silver Spring, Md.) The Variation of the Geomagnetic Activity Recurrence Interval with the Solar Cycle--A Chree-method analysis of geomagnetic activity as a function of phases of the solar cycle (sunspot latitude variation) was made with a combination of variables heretofore unreported. The results obtained indicate that the period for the recurrence of geomagnetic activity has a greater range than the 27 to 28 days obtained by previous investigators employing the Chree method. This particular analysis gave values for the recurrence period ranging from 26 to 29 days. The average period for pre-sunspot minimum years was 26.6 days and for post-sunspot minimum was 28.7 days. This range of values corresponds to the range of sunspot synodic periods. The study encompassed the years 1932-46 during which two sunspot minima occurred. The feature of this analysis differentiating

it from the work of others was the combination employing a large range of "C" values in the disturbed and in the quiet-day categories, and the breaking of the sunspot cycle into groups consisting of two and three consecutive years.

(19) C. Gaibar Puertas (Laboratorio de Geología, Universidad de Barcelona, Barcelona, Spain) Increase of the Earth's Magnetization--All investigations conducted to date on the magnetic state of the Earth have invariably led to the conclusion that during the last hundred years the magnetic attraction of our planet has been diminishing at the rate of 1/1,500 annually. In this research work the present magnetic state of the Earth as compared with preceding periods reveals that the absolute value of attraction or magnetization shows a notable increase since the period close to 1930. Finally, geographic distribution, as shown by signs and gradients of the secular variation caused by the geomagnetic intensity, is considered and analyzed. The isoporic maps demonstrate the phenomenon of terrestrial magnetism being produced by a geographic expansion of the positive Euroasiatic isoporic focus, inasmuch as the gradients of variation have experienced simultaneously heavy increases. Similarly, the negative gradients as revealed in a sector, each time more limited, have shown quite an intensive degradation.

SECTION OF OCEANOGRAPHY

(1) W. Armstrong Price (Department of Oceanography, A. and M. College of Texas, College Station, Texas) The Status of Geological Oceanography in the United States--After a century of considerable, though sporadic, output, geological oceanography is still in a pioneer stage, but with a strong demand for its services. Theory and techniques seem adequate for attack on current problems as finances are made available, though trained workers are scarce. Oceanic problems that can be solved by geology alone belong to marine geology, but those requiring a synthesis of marine sciences, including oceanography itself, belong to geological oceanography. In this category, the investigator finds techniques, instruments, and facilities developed by oceanographers with a body of colleagues experienced in coping with the common environment - the ocean. Geological oceanography is not a mere adjunct to physical oceanography, but has its own distinctive problems. It is at home in some fields, as in the shallower oceanic and estuarine waters, which physical oceanography is just now beginning to develop. The geological oceanographer provides liason between such phases of geology as stratigraphy, diastrophism, geomorphology, geochemistry, geochronology, paleontology, Pleistocene geology, and sedimentation, and the other branches of oceanography - chemical, biological, meteorological, and physical.

(2) C. W. Thomas (U. S. Coast Guard, St. Louis, Mo.) Physical and Biological Investigations in the Bering Sea and Portions of the Arctic Ocean, 1948--On the Bering Sea Patrol, in the summer of 1948, an oceanographic program was undertaken in the Bering, Chukchi, and Beaufort Seas, which was designed to provide basic scientific information to add to the general navigation and operational information in these waters. The investigations were contingent upon, and subordinate to, assigned operational and logistic tasks of the U. S. Coast Guard Icebreaker Northwind. Wherever possible, measurements were made of the thermal conditions, salinity, and depth of the water. In addition, current and ice observations were made during which the four and eight meter layers of sea ice were explored. The sea floor was investigated from bottom samples obtained by means of Underway Scoop-fish. Biological populations, both plankton and benthos, were also investigated.

(3) J. R. Longard and R. E. Banks (Defence Research Board, Naval Research Establishment, Halifax, N. S., Canada) Wind-Induced Vertical Movement of the Water on an Open Coast--The effect of winds on the vertical structure of the water column near the Atlantic coast of Nova Scotia is discussed. The analysis is based on twice-daily bathythermograms taken at Sambro Light Vessel. This vessel is located in 50 fathoms of water ten miles offshore in the vicinity of Halifax. Strong easterly winds blowing for more than half a day are shown to cause such a shoreward movement of the light surface water that the bottom water may be entirely displaced for at least ten miles offshore. Evidence is presented that this is a wind-driven effect and is not necessarily due to the presence of a low-pressure area in the vicinity.

(5) W. H. Munk (Scripps Institution of Oceanography, La Jolla, Calif.) Note on the Dynamics of the Antarctic Circumpolar Current--Unlike all other major ocean currents, the Antarctic Circumpolar Current probably does not have sufficient frictional stress applied at its lateral boundaries to balance the wind stress. The balancing stress is probably applied at the bottom, largely where the major submarine ridges lie in the path of the current. The meridional circulation provides a mechanism for extending the current to a large enough depth to make this possible.

(6) William S. von Arx (Woods Hole Oceanographic Institution, Woods Hole, Mass.) Surface Velocities in the Gulf Stream--An analysis is made of 1284 electromagnetic observations of the surface velocity of the waters in and adjacent to the Gulf Stream obtained during the multiple ship survey of June 1950. For independent comparison with these data, simultaneous current measurements were derived from the differences between hourly Loran fixes and dead-reckoning positions. The ratio of current magnitudes given by the two methods is used to derive an electrical estimate of the thickness of the layer of water in motion both in sections across several landward and seaward meanders of the Gulf Stream and along its length between 74° W and 50° W longitude.

(8) John C. Ayers (Cornell University, Ithaca, N. Y.), Dean F. Bumpus, and Alfred C. Redfield (Woods Hole Oceanographic Institution, Woods Hole, Mass.) The Fresh-Water Exchange of Great South Bay, Long Island--From measurements of the movement of fresh water out of Great South Bay through Fire Island Inlet and the passage leading into Moriches Bay, and records of the rainfall on the watershed and the flow of the tributary rivers, the following balance sheet has been drawn for the movement of fresh water into and out of the bay.

	cu ft/day	per cent
Rainfall on watershed	75.6×10^6	100
Evaporation	11.0×10^6	14.5
Ground-water seepage	50.7×10^6	67.1
River flow	13.9×10^6	18.4
Loss by tidal exchange	64.6×10^6	85.5

It is assumed that over the bay itself evaporation equals precipitation. Exchanges with South Oyster Bay are neglected. The result shows the great importance of ground-water seepage relative to river flow in supplying water to the bay and emphasizes the unreliability of employing river-flow data in estimating the flushing of estuaries surrounded by sandy watersheds. Measurements of the rainfall, river flow, ground-water elevation, and salinity of bay water during a period of five years show a correlation in their seasonal fluctuations. The flushing time for Great South Bay is estimated to be 48 days.

(9) W. N. Bascom (Department of Engineering, University of California, Berkeley, Calif.) Observations of Water Temperature, Wave Steepness, and Beach Width, Carmel, California--Observations on the water temperature in Monterey Bay and the beach width at Carmel, California, are correlated with the wave characteristics as determined by the forecasting procedure.

(10) Sidney H. Upham (U. S. Navy Hydrographic Office, Washington, D. C.) The Electrical Wave Staff - A Deep-Sea Wave Measuring Instrument--An instrument has been developed for obtaining recordings of wave heights and periods in deep-sea areas. This instrument is essentially an adaptation of an electrical step-resistance gage to a 50-foot spar buoy damping disk system. The electrical wave staff is designed to record a wave trace in water whose depth is greater than half of the wave length. Consideration is being given to further developing the instrument for use with a radio-buoy link system.

(11) Dale F. Leipper (Department of Oceanography, Texas A. and M. College, College Station, Texas) Progress in Oceanography at Texas A. and M. College--Since the last Annual Meeting of the American Geophysical Union, the Department of Oceanography at Texas A. and M. has initiated full graduate curricula leading to the Master of Science and Doctor of Philosophy degrees. There are separate curricula for each of the five aspects of oceanography: the biological, the chemical, the geological, the physical, and the physical and meteorological. New research projects conducted by the Department through the Texas A. and M. Research Foundation include a study of marine pipe-line problems sponsored by the United Gas Pipe Line Co. of Shreveport, La.; a survey of the oceanography and meteorology of the Gulf of Mexico with appropriate analyses of the data collected, an analysis of the transfer processes operating at the boundaries of the oceans, and a study of the atmospheric influences upon the temperature structure of the oceans sponsored by the Office of Naval Research; and additional studies in biological oceanography sponsored by a group of seven Gulf Coast oil companies. The program in oceanography at Texas A. and M. involves 20 full-time and 17 part-time persons. Fourteen graduate students are now majoring in oceanography and 17 are minoring. Twelve graduate assistantships are available for 1951-1952.

(12) I. I. Schell (Woods Hole Oceanographic Institution, Woods Hole, Mass.) The Problem of the Iceberg Population in Baffin Bay and Davis Strait and Advance Estimate of the Berg Count off Newfoundland--The iceberg population in Baffin Bay and Davis Strait is intimately connected with the problem of advance estimating the berg count off Newfoundland and the safety of local and trans-Atlantic navigation in that area. It is suggested that, in addition to counting the number of bergs in different sectors of Baffin Bay and Davis Strait, and deducing their movements from the presence

of certain concentrations a year or two later in other areas, the bergs be sprayed by color dust from the air. The marked bergs could then be searched for by plane and, from their movements, estimates made as to their course of travel, average speed, and mortality. A successful tracking of the bergs in conjunction with wind data should provide also valuable information on the circulation of the waters in that area.

(13) Richard James (New York University, New York, N. Y.) A Test of Wave Forecasting Methods Applied to Long Branch, New Jersey--It is shown that the New Jersey coast is a good location for a test of the wave-generation part of the Sverdrup-Munk forecasting theory. Wave height and period were forecast every four hours for six months. All the methods used, including an analogue system similar to that used in weather forecasting, are described and their comparative accuracy discussed. It is concluded that the described methods, based mainly on the Sverdrup-Munk wave-generation theory, are accurate for height forecasts and that further study is needed in order to forecast periods.

(14) Willard J. Pierson, Jr. (New York University, New York, N. Y.) The Propagation of a Finite Wave Train in Infinitely Deep Water--Given that the free surface of an infinitely deep ocean is represented by $\eta(t) = A \cos 2\pi t/T$ when $-(n + 1/4)T < t < (n + 1/4)T$, and by $\eta(t) = 0$ otherwise, and given that the train of waves which is finite in duration described by these conditions is traveling in the positive X direction, then it is possible to find the free surface as a function of space and time. The solution of the problem which has been obtained by the application of Fourier's Integral Theorem shows that the apparent period of the wave train is unaltered as the train travels along, and that the ends of the wave train are modulated by appropriate forms of the Fresnel Integrals. The gradual change in form of the envelope of the wave train is described.

(15) S. E. Rauch (Santa Barbara College, University of California, Santa Barbara, Calif.) Introductory Theory for a Rayleigh Disc Wave Direction Indicator--Rayleigh has shown that a circular disc placed in a moving fluid is acted upon by a torque which tends to move the normal to the disc in the direction of the fluid flow. A study is presented for the use of a disc when it is acted upon by two simultaneous wave trains. Computations are presented to determine the equilibrium angle and the magnitude of oscillation due to typical sea and swell wave motions. The effects of depth below the surface of water, the ratio of amplitudes of the two wave motions, and the moment of inertia of the wave direction indicator are studied.

(16) Frank MacDougal (U. S. Navy Hydrographic Office, Washington, D. C.) Correlation of Heights of Observed and Computed Local Wind Waves in North Atlantic Ocean and Mediterranean Sea--An additional proof of the validity of the Sverdrup-Munk technique for forecasting the height of the local wind waves at deep-sea locations is presented. The proof makes use of the correlation coefficient and the similarity of the frequency function curves derived by the use of Craig's method of determining the Pearson-type curve that is involved.

SECTION OF VOLCANOLOGY

(1) E. G. Zies (Geophysical Laboratory, Carnegie Institution of Washington, Washington, D. C.) Volcanic Activity at Santiaguito, 1932-40; a Geochemical Study--In October of 1902 an eruption of great intensity on the west flank of Santa Maria in Guatemala revealed that potentially active igneous materials were present within the supposedly extinct volcano. The explosive phase of the eruption lasted about three days and formed a crater at an elevation of 7000 ft. This activity abated rapidly and it seemed as if the volcano had again become dormant. In 1922, however, a viscous lava was seen to rise slowly and quietly in the crater formed in 1902. Within a period of three years the new volcano of Santiaguito was built up to a height of about 800 ft within this crater and had become a conspicuous feature of the western slope of Santa Maria. Fortunately, we have a very good pictorial record of its growth during this period, made by G. Hurter of Quezaltenango. The activity has continued without break and still shows no signs of abatement. The height of the volcano above the crater floor has changed very little since 1925, but its girth has increased enormously.

Santiaguito has been formed by the extrusion of (a) hot (750°C) clastic material, (b) viscous monolithic masses, and (c) viscous flows confined to its slopes. In 1940, type (a) was the dominant type of extrusion. The bulk of the lava is hypersthene andesite which acts as host to many tightly held inclusions of hornblende andesite. In some of the viscous flows (extrusion type c) the inclusions are so abundant as to make up 25 pct of the rock mass. They vary from a few tenths of a millimeter to several inches in maximum diameter. Occasionally, loosely held, almost basaltic inclusions are also found. Xenoliths of granodiorite occur in the rubble of the base of the southern slope. Flow structure is common in the host rock but not in the inclusions. As a rule, the host rock is very porous and glassy, but sometimes it is compact, as if "fire-polished." An extruded

monolithic mass in the northeast portion of the dome has devitrified and contains much cristobalite.

The lava extruded in 1940 had a composition intermediate between that of the host rock and inclusions extruded prior to 1932. Chemical analyses show that the ratio of ferric to ferrous oxide in the host rocks and in many of the inclusions varies considerably. This difference is reflected in the color of the specimens and also in the color, as seen under the microscope, of the hornblendes in the inclusions. Many of the features noted above can be referred to the fact that we are dealing with a lava that has been differentiating under the Earth's surface, and slowly and intermittently extruded.

Fumarolic activity has persisted from the first appearance of Santiaguito. A line of fumaroles on the eastern slope was subjected to detailed study. The temperatures of the exhalations ranged from 75°C to 390°C.

Analyses of samples of water made by condensing fumarolic steam revealed the presence, per liter, of 5 to 15 grams of hydrochloric acid, 0.5 to 8.0 g sulfuric acid, 1.8-27.0 mg hydrobromic acid, 1.7-8.0 mg hydriodic acid, 19.0-77.0 mg hydrofluoric acid, and 5.8 mg boric acid. Sulfur dioxide was also present. Hydrogen sulfide was not found in any of the fumaroles. In one of the areas sulfur vapor was abundant. There seems to be a relation between the amount of the various acid constituents per liter and the temperature of the escaping steam; at lower temperature (ca 250°C) the steam is richer in hydrochloric acid than at elevated temperatures (ca 390°C), whereas the reverse holds for sulfuric acid. The acid gases together with steam alter the andesite and form many incrustations which were studied by combined chemical, microscopic, and X-ray analysis.

In spite of the prevalence of hydrochloric acid in the fumarolic gases, chlorides as incrustations are found only in areas where the temperature is well below 100°C; practically all of this acid goes off into the atmosphere. Such chlorides as are formed eventually find their way into the drainage waters. The incrustations are dominantly sulfates.

Sulfur, orpiment, selenium, and tellurium are abundant in some areas. In others, where air seems to be aspirated through the porous volcanic edifice, they are absent. In many areas the andesitic rock is completely altered, but much of the original structure is retained. For instance, examination of a thin section of gray indurated incrustation revealed the ghosts of plagioclase phenocrysts. X-ray analysis combined with chemical separations show that anhydrite, alunite, low-temperature cristobablite, anatase, rutile, and pyrite are present. Alunite and cristobalite are the dominant constituents. Other types of incrustation were formed by dehydration, by hot steam, of sulfates leached from areas subjected to the type of alteration described above.

Santiaguito has been continuously active for almost 30 years and there are at present no indications that this activity is waning. We therefore have an unusual opportunity for further geochemical study of a going concern.

(2) Howel Williams (University of California, Berkeley, Calif.) The Great Eruption of Coseguina, Nicaragua, in 1835--The outburst of Coseguina in 1835 has generally been regarded as the most violent eruption within historic times in the Americas. Pitifully little is known, however, concerning the character of the activity or of its products. Estimates of the volume of ejecta range up to 150 cubic kilometers. Ash fell over an area 1,700 mi in diameter; the noises were heard in Jamaica and Bogotá. The eruption began on January 20 after brief, preliminary quakes, and reached its climax on the night of January 22-23. By January 27, the ash-fall had essentially ended. During this short interval, the top of the mountain was destroyed, leaving a crater between one and one and one-half miles across, and between 1,500 and 2,000 ft deep.

Previous estimates of the amount of ejecta are too liberal; probably not more than ten cubic kilometers were discharged. The magma involved was basaltic, containing about 25 per cent of bytownite phenocrysts and four per cent of hypersthene, augite, and iron ore. Large bombs and lithic blocks are astonishingly rare. Almost all of the ejecta are finer than sand, even on the mountainsides. Most of the material fell in showers from the air, but in the closing stages there were glowing avalanches. Lava flows were absent. The volume of lithic debris is much smaller than that of the vanished mountaintop; accordingly, collapse was the prime cause for the present crater. Equally violent explosions of basaltic magma are uncommon; these indicate extraordinary ultra-vesiculation, most of the magma being expelled as fine spray.

(3) Kenzo Yagi (Geophysical Laboratory, Carnegie Institution of Washington, Washington, D. C.) Formation of Syowa Sinzan, a New Volcano in Japan--The parasitic volcano Syowa Sinzan formed during 1943-1945 on the eastern foot of Usu Volcano in Hokkaido, Japan. This new volcano is composed of a "dome" resting on a circular platform-shaped "roof mountain." The latter is an upheaved part of the ground, about one kilometer in diameter, and consists mainly of the somma lava of Usu Volcano, while the former is a new lava mass, protruding through the roof mountain. The height of the dome is 405 m above the sea level, or about 350 m above the surrounding ground. This new lava mass emerged in already solidified state; it is thus a "belonite," resembling the famous spine of Mt. Pelee.

The new lava is a hypersthene dacite with phenocrysts of andesine (An_{39-50}) and hypersthene (En_{55}) in a groundmass of andesine, cristobolite, quartz, hypersthese, and other minerals, and is characterized chemically by high lime and very low potash content. Petrologically it resembles closely the dacite lavas of other domes of Usu Volcano. The lava of the roof mountain is olivine-augite-hypersthene andesite, quite similar to the other somma lavas of this volcano. The lava sometimes carries large crystals of calcic plagioclase (An_{89-90}) which are believed to be xenocrystic in origin. Lavas of composition intermediate between the somma lavas and the dome lavas are entirely lacking in Usu Volcano and related domes. Complete similarity of the dome lavas in spite of their considerable age differences suggests that there has been no appreciable differentiation in the magma reservoir since these dome lavas began to form.

(4) Ray E. Wilcox (U. S. Geological Survey, Washington, D C.) Progressive Chemical Changes in the Lavas of Parícutin Volcano, Mexico--Analyses of 16 specimens of Parícutin lavas erupted at various times since the birth of the volcano indicate a progressive change in chemical composition of the emerging material. The proportion of silica has increased fairly steadily from 54.7 pct in 1943 to 59.0 pct at the beginning of 1950. Potash and soda increased while alumina, total iron, and lime decreased. Magnesia changed little until the last half of 1947 when it decreased rapidly from 5.6 pct to 4.0 pct, thereafter decreasing slightly. The sudden decrease in magnesia was accompanied by divergences from the normal trends of most of the other oxides. The lavas have passed, without significant interruption of eruptive activity, through the range of basaltic andesites and have approached the character of normal andesite. There has been a corresponding increase in apparent viscosities of the successively erupted material. Most striking petrographic change has been the decrease in amount of olivine and increase in hypersthene.

Gravitative differentiation accounts adequately for such features as the sudden decrease of magnesia, which coincided with a similar decrease in the amount of high-magnesia olivine phenocrysts, and presumably this has been a continuing process. Partly resorbed granitic and quartzose xenoliths in the lavas, on the other hand, suggest that assimilation has also been a factor. The conclusion offered at this stage of the study is that both mechanisms have been operating to produce a non-homogeneous magmatic body, the composition of which continues to change.

(5) Hatten S. Yoder, Jr. (Geophysical Laboratory, Carnegie Institution of Washington, Washington, D. C.) Influence of Volume Change on Magma Production and Extrusion--A slab of basaltic rock, $400 \times 25 \times 1$ mi at a depth of 25 mi (base of crust) is considered. The beginning of melting of basalt at one atmosphere is assumed to be 1000°; the change of the beginning of melting of basalt with pressure is estimated to be 10°C/1000 bars (based on unpublished data); and the slab, according to the assumed geothermal gradient, is at a temperature 75° in excess of that required for melting at one atmosphere. On release of 5000 bars pressure, by gentle arching of the superincumbent rock for example, six per cent of the slab melts, consuming the adiabatically available heat (specific heat = 0.30; heat of melting = 100 cal/gm). With the arching process or through some other mechanism, tensions are built up; fractures develop accompanied by earthquakes having shallow (20-25 mi) centers. The tectonic earthquakes which usually precede the great extrusions are indicative of the relief of stress but not necessarily the relief of hydrostatic pressure.

The volume change on melting for basalt is 11.5 pct; the slab will increase in volume by 70 mi^3. The space for this increase in volume may be obtained by further arching of the overlying rock, or, by some of the magma rising in the fractures. Consider the second possibility: The 70 mi^3 of molten rock can fill a channel 150 mi long and 100 ft wide from the bottom of the crust to the surface. If the crystal mush rises in bulk, the channel will overflow since, in rising, the pressure is further reduced, more melting takes place, and the ratio of liquid to crystals increases. The great basaltic lava flows have poured out of fractures; the linearity of the great volcanic mountain chains also attests to fracture control. Further considerations indicate that the lava will flow out non-explosively for a considerable time along the entire channel or out of chance openings. The heat effects, role of volatiles, and compositional changes in this mechanism are also discussed.

No matter how a magma is produced from solid rock in the crust, by heat from a local hot spot, by relief of pressure, by actual unloading, the considerable volume change accompanying the phase change plays an important role in the extrusion of the magma.

(6) Francis R. Boyd and George C. Kennedy (Harvard University, Cambridge, Mass.) Some Experiments and Calculations Relating to the Origin of Welded Tuffs--Petrographic study of salic volcanic rocks in recent years has revealed a class of rocks which appear to be normal lavas in hand specimen, but which show apparently deformed pyroclastic textures when examined in thin section. Such rocks have been variously called welded tuff, collapsed pumice, or ignimbrite. They have been generally interpreted as the product of a nuée ardente type of eruption. Extreme temperatures of formation have often been assumed. Samples of rhyolitic pumice from Mono Craters were crushed and subjected to various temperatures and differential pressures in a bomb. The pumice was found to weld at temperatures ranging from 775° to 900°C. Textures so produced are

very similar to those of welded tuffs. Assuming a welding temperature of 800°, thermodynamic calculations indicate an original magma temperature of approximately 850°. Exothermic gas reactions are believed to be neither probable nor necessary. Such a magma, if at its liquidus, must contain approximately 4.8 pct H_2O, and would have an internal vapor pressure of 700 atmospheres.

(8) J. Verhoogen (University of California, Berkeley, Calif.) The Temperature at the Boundary of the Earth's Core--A method is suggested to determine, from seismic data and Bullen's density distribution, the temperature at the bottom of the mantle as a function of the "normal" density of the material existing at that depth. Assuming a normal density $\rho_0 = 4.15$, a preferred temperature T = 2,200°C is obtained. This value would indicate that the thermal gradient in the lower mantle is at present close to the adiabatic value.

(9) C. L. Jones, P. H. Dodd, and R. M. Garrels (Northwestern University, Evanston, Ill.) Crystallization and Rock Textures--Crystallization of unseeded solutions of a number of ionic salts, under similar conditions, showed that they all crystallized at the same coefficient of supersaturation. The actual coefficients of supersaturation differed from experiment to experiment, but they ranged around a definite mean. In completely unstirred solutions of potassium nitrate, the time interval to the first crystal nucleus is inversely proportional to the coefficient of supersaturation, and is directly proportional to the radius of a particle of critical size. A particle of critical size is one that will neither dissolve nor grow in a supersaturated solution. Some applications of the data to the problem of determining original textures of chemical sediments and igneous rocks are suggested. Coefficient of supersaturation as used in this paper is $(S_1 - S_0)/S_1$, where S_1 is the actual concentration of a salt in solution, and S_0 is the concentration of coarsely crystalline salt in equilibrium with the solution.

(10) E. Wm. Heinrich (Department of Mineralogy, University of Michigan, Ann Arbor, Mich.) Structural Features of Some Fennoscandian Pegmatites--Granite pegmatites of Finland, Sweden, and Norway show many internal structural features similar to those reported recently for pegmatites of the United States. Zoning may be conspicuous with the development of border, wall, intermediate zones, and cores. In these units microcline is the predominating feldspar in the inner zones, whereas oligoclase is more abundant in the border zone and in some wall zones. In other pegmatites, units of secondary origin, such as veins and replacement bodies, are strongly developed, and in these units plagioclase either as cleavelandite or sugary albite or both is the more abundant feldspar. Especially noteworthy under this type is the Varuträsk pegmatite, near Boliden in northern Sweden, in which occur commercial quantities of rubidium microcline, petalite, pollucite, spodumene, amblygonite, and lepidolite, together with many other rarer mineral species. Rare-earth pegmatites, such as those of Ytterby, Sweden, or of the Iveland district, Norway, are characterized by large parallel biotite sheetings, which serve as loci for concentrations of the rare-earth minerals. Beryl crystals from several complex pegmatites in the Kimito district of southwestern Finland are noteworthy for their "reaction" rims of sericite, chlorite, chrysoberyl, and sillimanite. Pegmatites that were intruded into amphibolite have developed a contact metamorphic aureole of biotite. Unusual contact effects occur where pegmatite crystallized in eulysite and produced coarse marginal hypersthene and garnet. Syenitic pegmatites of the Stavern area, Norway, also are zoned although the units are not as sharply defined as in granitic pegmatites. In the Langesundfjord area of Norway, some nepheline syenite pegmatites display hanging-wall zones in which aegirine crystals, some of which are several inches in diameter and most of which are twinned on (100), are exceedingly abundant and generally oriented with their c axes normal to the contact.

(11) Patrick M. Hurley (Massachusetts Institute of Technology, Cambridge, Mass.) Heat Flow and Chemical Segregation of the Mantle--Age measurements on basement crystalline complexes suggest that silica-alumina-alkali rich material has continued to appear at the Earth's surface throughout geologic time with no lessening of activity in the near past. Data on radioactive heat production in rocks versus the density afford estimates of the total heat production in continental crustal rocks. At this point in the progress of radioactivity measurements on rocks it appears that heat production from rocks above the Mohorovicic discontinuity accounts for over 70 pct of the total surface heat flows. Temperatures at the Mohorovicic discontinuity are therefore indicated to be less than 300°C for low shield areas and less than 800°C for high mountain areas. Material below the discontinuity cannot have more than a very low heat production without exceeding the measured surface heat flows.

Measurements on the Oregon basalts give values too high to permit the basalt to exist as a part of a permanent extensive layer below the discontinuity, and at the same time there is difficulty in achieving the temperature of 1100°C or so for the molten basalt if it occurred above the discontinuity. This argument is even more pressing in the case of oceanic volcanic islands. It is therefore suggested that at least some basalts are concentrates or extracts from partial

fusions at depths of at least several hundred kilometers within the mantle, brought to the surface by convection, and representing a continuing source of alumina, alkalis, and other elements for continental growth.

SECTION OF HYDROLOGY

(1) Hermann von Schelling (Naval Medical Research Laboratory, U. S. Submarine Base, New London, Conn.) Most Frequent Particle Paths on the Unit Sphere--The following definition of most frequent particle paths on any surface is developed in section I: A particle moving on a given surface may have a chance of changing its direction after each element Δs of the arc length by a random angle ϕ, where ϕ is normally distributed. We know that the geodesic curvatures are $K_g(s_0)$ and $K_g(s_1)$ for two given values of the arc length s. We seek for the most frequent particle path which satisfies these conditions. It can be proved easily that

$$\int_{s_0}^{s_1} K_g^2(s)\, ds = \text{minimum}$$

for these curves. The spherical most frequent particle paths are determined in this paper. The plane orbits of this type have been discussed in a paper in the issue of the Transactions of April 1951 (pp. 222-226).

Section II contains the solution of $K_g = K_g(\beta)$, where K_g is the geodesic curvature, and β the geographical latitude. Section III yields the geodesic curvature of spherical most frequent particle paths. The coordinates of the orbits are given in Section IV, expressed by incomplete elliptic integrals of the first and third kinds. Finally, the general curves are discussed qualitatively in Section V; special cases are evaluated.

There are two main kinds of orbits. The first group is oscillating inside two symmetrical zones of the northern and southern hemispheres. The geodesic curvature is proportional to the sinus of the latitude. The curves have loops, but no points of inflection. The second kind of paths cross the equator which changes the sign of the geodesic curvature. The curves oscillate between the latitudes $+\beta$ and $-\beta$, and may or may not have loops. If any most frequent particle path runs to the north or south pole, the loop is reduced to a cusp at the pole. These special curves can be construed easily, since only an elliptic integral of the first kind is involved. Their arc length is proportional to the geographical longitude. Viewed from the poles, these particular orbits are always concave.

(2) Francis E. Swain (U. S. Bureau of Reclamation, Denver, Colo.) Determination of Flows in Interconnected Estuarine Channels Produced by the Combined Effects of Tidal Fluctuations and Gravity Flows--This paper presents a method for determining the variable flows in an estuarine channel system. The procedure makes use of a theory developed to establish the magnitude of "surge" or "bore" waves produced in canals by a disturbance of flow. The rate at which high and low water, as well as the strength and turn of the current, advance along an estuary is often so close to the rate of advance of a frictionless progressive wave in a channel of uniform dimensions that this value is frequently taken as the normal rate of progress of the tide. This fact suggested the use of the bore or surge wave theory in the analysis of estuarine channel flows since the tidal variations may be represented as a series of small incremental changes in the height of the water surface which in turn produce small bore waves. With the tidal variations known at a given location in the interconnected system, those at other points in the system may be determined. The effects of friction, channel cross-section, and channel length may be taken into account.

The friction effects are treated individually in each separate channel by assuming the entire friction to be concentrated at a barrier at some section in the channel, usually at the mid-length of the reach. The combinations and reflections of the several individual waves arriving at a junction of two or more streams are treated in a manner similar to that employed in the theory of water hammer for branch connections.

The resultant flows produced by the combined action of the tides and gravity are determined by computing the flows due to gravity alone initially and superimposing the flows produced by the tidal fluctuations. The gravity flows represent essentially initial conditions from which the combined analysis proceeds. The initial flows are determined by a gravity network analysis using standard procedures. The analytical method and results have been checked using a graphical procedure similar to that employed for the solution of water-hammer problems by graphical means. The method has also been checked using electric-analog computers.

(3) A. Craya (Iowa Institute of Hydraulic Research, State University of Iowa, Iowa City, Iowa) Evaluation of the Critical Regime in Stratified Flow--A fundamental role in the study of flow in open channels is played by the concept of critical regime. This concept has recently been generalized by Rossby for gravity currents due to density stratification, the implications of which should

provide a better understanding of the distribution of winds, oceanic currents, and flow due to density stratification in general. This paper interprets this generalized concept from the hydraulics point of view. Consideration of the momentum principle and of the energy principle permits the formulation of two integral expressions for the cross-section of a stratified current, the value of which can only decrease. These integrals nevertheless have a minimum value which is attained for a certain thickness of the current and for a certain velocity distribution, which by definition represent the critical regime. Critical regimes obtained by the two foregoing principles are not identical, though very nearly so.

Concerning the shape of the critical distribution, of velocity the following cases must be distinguished: (1) For a submerged current, the velocity is zero at both extremities of the section and reaches an intermediate maximum. (2) For a surface current of which the topmost streamline is restricted to a condition like constant level or constant energy, there is a maximum velocity some distance under the free surface. (3) For a surface current without any restriction on the displacement of the topmost layer, the maximum velocity is reached at the free surface. The significance of these critical regimes is to be interpreted as a tendency of a gravity current with density stratification towards the critical state, in the same manner as for the flow in an open channel with horizontal bottom.

(4) Mahdi S. Hantush (College of Engineering, Baghdad, Iraq) and C. E. Jacob (University of Utah, Salt Lake City, Utah) Non-Steady Green's Function for an Infinite Strip of a Leaky Aquifer--This paper presents the theoretical development of the non-steady drawdown distribution induced by a well located in an infinite strip, starting from rest and discharging steadily thereafter. The well is drilled into a leaky aquifer throughout which the initial drawdown is zero. The solution, which is obtained for the case where the head is kept constant along the boundaries of the strip, constitutes the Green's function of the first kind for the infinite strip. The Green's function of the second kind for the same region is also obtained. It is shown that, if the Green's function for a given region is known, then the drawdown distribution within the region can be obtained if the boundaries are subjected to head or flux, or both, which vary with time. A table and a curve are given for one set of assumed values of the parameters of the system.

(6) F. A. Huff and G. E. Stout (State Water Survey, Urbana, Ill.) A Study of Thunderstorm Rainfall on Small Watersheds--Area-depth relationships on basins of 280, 95, and 5.2 sq mi are discussed, using data collected on dense rain-gage networks in central Illinois during 1948-1950. The effect of gage density on the accuracy of areal mean rainfall calculations is demonstrated. Frequency distributions of areal mean rainfall with respect to storm type and storm intensity during the three-year period are determined.

(8) E. J. Gumbel (441 Ocean Ave., Brooklyn 26, N. Y.) The Circular Normal Distribution--The usual statistical theory of cycles requires a complicated mathematical setup. Even acyclical phenomena can easily be analyzed as a series of cycles which do not correspond to reality. In addition, one cannot be sure whether a cycle has been detected or invented. Therefore, the theory of cycles is a natural field for pseudo-scientific investigations. In contrast to these procedures, one asks for statistical distributions corresponding to an existing cycle, that is, the distribution of a variate such as an angle confined in the interval from zero to 2π, or events which are distributed over the 24 hours of a day, or the 12 months of the year. In analogy to the classical derivation of the normal distribution, the statistical theory based on a procedure of R. von Mises postulates that the mean direction should also be the most probable one. This leads to a symmetrical distribution, namely, an exponential function of the cosine of the direction. It contains two parameters, the mean direction and a measure of concentration k which, estimated by the method of maximum likelihood, is obtained from the strength of the resulting vector. The case $k = 0$ leads to the circular uniform distribution while for large values of k, about 4, the distribution approaches the linear normal one. Tables of the distribution and the probability function for 72 angles and all values of k from 0.1 to 4.2 were prepared to nine significant decimals by J. A. Greenwood and D. Durand. The theory gives a good fit to the observed wind directions, distributions of earthquakes over the day, the monthly distributions of temperatures, dew points, rainfalls, evaporations, storms, runoff, floods, ground-water levels, sunshine, solar constant, magnetic fields, marriage rates, birth rates, death rates, accidents, and egg production. The circular normal distribution can serve as a model for the statistical analysis of cycles, and will give a method for determining true periodicity.

(10) Robert F. Black (Alaska Terrain and Permafrost Section, U. S. Geological Survey, Washington, D. C.) Some Techniques and Equipment for the Study of Ground Ice and Permafrost--During the period September 1949 - November 1950, established petrofabric and petrographic techniques for the study of metamorphic and igneous rocks and of glacial ice were modified as the need

arose to initiate a microscopic study of ice wedges and other forms of ice in permafrost at Barrow, Alaska. Equipment and techniques similar to those currently used in the study of glacial ice were employed to prepare semi-permanent and temporary thin sections, one to ten inches square, of ice and soil. The techniques are flexible and can be modified commensurately with the available power or hand tools or with the ability and inclination of the technician. They are described in detail. Hand augers, drilling bits, picks, saws, and other equipment and methods used in sampling the ground ice are discussed. Also treated are the equipment and techniques used in measurement of ground contraction, liquid content of permafrost, snow density and porosity, weather data, and near-surface ground temperatures for the purpose of determining data on ground contraction, thermal diffusivity in frozen ground, and heat exchange of ground and atmosphere.

(12) Joel E. Fisher (25 West 43rd St., New York, N. Y.) Control of Cycles of Glaciation by Changes in the Flow of Internal Heat of the Earth--By combining recent developments on (1) compressibility of solids (P. W. Bridgman), (2) application thereof to interior densities of the Earth (K. E. Bullen), and (3) possibilities that universal gravitation has varied inversely with the age of the universe (Pascual Jordan), there is presented the conception of an Earth expanding over all time. Such an expanding Earth implies (thermodynamically) a cooling of its mass by 3000°C in some 3,000,000,000 years. Recent radioactive studies imply that a (non-expanding) Earth should have increased in temperature about 3000°C from disintegration of radioactive minerals over that same time. The two opposing controls on its temperature would therefore appear to very nearly balance each other. However, changes may have taken place in specific heat, or in heat conductivity of minerals in successive interior shells of the Earth, due to transition of such successive shells, from one "state" to another, as pressure decreased. Such changes in specific heat, or of heat conductivity, are shown to be theoretically sufficient to vary the flow of interior heat of the Earth, up to its surface, by at least 25 pct of its present-day amount (60 gr cal cm^{-2}/year.

It is then shown thermodynamically that, given an unchanged climate, a decrease of some 25 pct in the supply of these 60 gr cal cm^{-2}/year beneath any glacier (which is in equilibrium as to ablation and accumulation) will throw that glacier over into a condition of expansion; and, if a wide enough land area is affected by that decrease in flow of interior heat, the expansion of such a glacier may continue indefinitely up to continental ice-cap limits. A return to an increased flow of internal heat is shown to diminish quickly the area of glaciers, climatic conditions remaining unchanged.

(13) William O. Field, Jr. (American Geographical Society, New York, N. Y.) Recent Glacier Variations in Glacier Bay, Alaska--Throughout the Nineteenth Century and up to the middle 1920's the largest glaciers of Glacier Bay were in almost continuous recession. A few advances were recorded but they were of short duration. In the last quarter century, a number of the glaciers have continued to recede very rapidly, while others have experienced little if any net recession, and at least two large glaciers have advanced about a mile and are still advancing. Several small glaciers have also experienced startling oscillations which have been recorded by various observers and in aerial photographs. Since no meteorological records are available in Glacier Bay itself, it is difficult to determine the causes of these variations, and one can only draw inferences from a study and correlation of the behavior of the termini. For any adequate understanding of these phenomena, there is need of a long-range program of detailed glacio-meteorological studies at the upper levels corresponding to the elevation of the névé areas.

(15) C. H. M. van Bavel and A. W. Waltner (North Carolina State College, Raleigh, N. C.) An Electrical Analogue for the Study of Diffusion Processes with Internal Gains or Losses--Processes of air and water transport in soils are not only activated by outside forces, like gravity, and resulting differences in potential, but also by internal consumption or release. If the movement is of the diffusion type, its description is a inhomogeneous partial differential equation of the Poisson type. Numerical solutions may be found with the aid of an electrical method of analogy. The method consists for one- or two-dimensional problems of constructing a tray, filled with a conductive liquid, with proper electrodes and insulating material as confining boundaries. At a number of points in the liquid electric current is admitted by means of point electrodes and the resulting potential distribution in the liquid is recorded. It was found that results were in substantial agreement with theoretically computed values. Possibilities of this method in various fields of research will be indicated.

(16) B. C. Goodell (Rocky Mountain Forest and Range Experiment Sta., Ft. Collins, Colo.) A Method for Comparing the Flow from a Pair of Experimental Watersheds--This paper briefly describes a method developed to predict the annual stream flow of one experimental watershed from that of another. The watersheds are not similar in size or in topographic characteristics. They are at similar elevations. It is possible to predict the stream flow for selected months or for

natural segments of the hydrograph. Likewise, the shape of the hydrograph and the total volume of flow can be established. Errors of prediction are discussed as well as the precision required to determine the effects of treatment which might be applied to an experimental watershed.

(17) Arnold B. Taylor and Harry E. Schwarz (U. S. Army, Corps of Engineers, Washington, D. C.) Unit Hydrograph Lag and Peak Flow Related to Basin Characteristics--Unit hydrograph lag and peak-flow values have been empirically related to basin characteristics and to the duration of rainfall excess. Basin characteristic data of 20 basins ranging from 20 to 1600 sq mi of drainage area and located in the North and Middle Atlantic States were used in the study. Unit hydrograph values were obtained from 65 runoff excess periods. The study indicates that the most significant basin characteristic factors were drainage-area size, length of longest watercourse, length to center of area, and equivalent main-stream slope. Graphs of the correlation studies are given and a method for determining equivalent main-stream slope is presented. A nomograph for the computation of synthetic unit hydrographs is included and is based on equations developed in the study. The data presented will aid in the determination of unit hydrographs for ungaged watersheds in similar areas.

(18) Harry F. Blaney (Division of Irrigation, Soil Conservation Service, Los Angeles, Calif.) Determining Evapotranspiration by Phreatophytes from Climatological Data--Before the available water resources of a drainage basin in arid and semi-arid regions can be satisfactorily ascertained, careful consideration must be given to the consumptive water requirements of phreatophytes (water-loving vegetation) and other types of natural vegetation and agricultural crops. The moisture requirements of natural vegetation are usually satisfied before water becomes available for irrigation and other purposes. Although evapotranspiration (consumptive use) by phreatophytes has been measured at various times and places during the past 40 years, very little data are available in most sections of the United States. This paper presents data on measured evapotranspiration by phreatophytes and describes a method of determining rates of water consumption in areas where no measurements except climatological data are available. Briefly, the procedure is to correlate existing evapotranspiration data with monthly temperature, monthly percentages of yearly daytime hours, and growing period. The coefficients so developed for different kinds of vegetation are used to transpose the evapotranspiration data for a given area to other areas for which only climatological data are available.

(19) John T. Koogler (U. S. Bureau of Reclamation, Amarillo, Texas) Phreatophyte Control on Irrigation Projects in New Mexico--Over 70,000 acres of salt cedar, cottonwood, willow, and baccharis are growing along stream channels or on irrigation projects in New Mexico, east of the Continental Divide. The greatest problem areas at present are the Middle Rio Grande Valley (Cochita to Elephant Butte Reservoir) and the McMillan Reservoir Delta Area on the Pecos River. Incipient growth has been noted above Caballo Reservoir on the Rio Grande, Alamogordo, and Avalon Reservoirs on the Pecos River and above Conchas Reservoir on the Canadian River. From experience with the rapid spread of the salt cedar in the McMillan Reservoir Delta, the area and density of growth in the other areas can be expected to increase rapidly. Under the Soil and Moisture Conservation Program of the Bureau of Reclamation beginning in 1948, a project was established to perform extensive field tests for the control of salt cedar in the McMillan Delta Area and to supply technical assistance to the irrigation projects in the region for the control of weeds and woody plants.

The salt cedar growth on the McMillan Reservoir Delta was first reported in 1914, and at present covers about 15,000 acres. It is estimated to use non-beneficially about 54,000 ac ft of water annually. In 1948 and again in 1949, the plant hormone 2,4-D was sprayed by airplane to 100 acres of salt cedar. By 1950 approximately 85 pct of the area sprayed was free of salt cedar growth. The total cost of the two spray treatments was about $12.50 per acre. On the Rio Grande Project, New Mexico, some irrigation canals were greatly reduced in capacity by growths of willows. A treatment, consisting of cutting the willows with a specially designed tractor-operated cutter and subsequent spray applications of 2,4-D, has proven to be very effective in the elimination of this growth. Costs of this treatment have averaged about $12.98 per bank mile. On the same project growths of cattails, rushes, and sedges have been greatly reduced in effectiveness by a combination of winter burning, early spring spray application of 2,4-D, and two or three summer spray applications of diesel oil fortified with pentachlorophenol and 2,4-D.

(20) S. F. Turner and H. E. Skibitzke (U. S. Geological Survey, Tucson, Ariz.) Use of Water by Phreatophytes in 2,000-Foot Channel between Granite Reef and Gillespie Dams, Maricopa County, Arizona--The following is a summary of data obtained in a study of transpiration by phreatophytes in the channels of the Salt and Gila Rivers, between Granite Reef and Gillespie dams, Maricopa County, Arizona. The study was made in the spring of 1950 by the U. S. Geological Survey in cooperation with the Corps of Engineers, United States Army. The kind and amount of

phreatophyte growth was mapped in the area covered by a proposed flood-control channel, 2000 ft wide, extending between the two dams. Most of the mapping was done from the air, using recent aerial photos. Transpiration by the phreatophytes was computed using the results of the mapping combined with water-use factors developed by experimental work done by the Geological Survey in Safford Valley, Arizona, during 1943 and 1944. Estimates of future phreatophyte use and of the amount of water that might be saved by clearing and maintaining the channel area were based on extensions of water-level graphs to include the next 50 years, and on the experimental work at Safford. The estimates were as follows: (1) total estimated transpiration from ground water at time of investigation - 29,000 ac ft per year; (2) estimated average transpiration from ground water, within the channel area, during period 1950-1999 (a) without Colorado River water - 22,200 ac ft per year, (b) with Colorado River water in 1960 - 29,900 ac ft per year; (3) estimated average water saving effected by channel clearing, 1950-1999 (a) without Colorado River water - 16,600 ac ft per year, (b) with Colorado River water in 1960 - 22,400 ac ft per year.

(21) T. W. Robinson (U. S. Geological Survey, Carson City, Nev.) Phreatophytes and Their Relation to Water in Western United States--Phreatophytes, plants that depend on ground water for their water supply, cover about 15 million acres in the 17 western states, and may waste as much as 20 to 25 million ac ft of water into the atmosphere annually. There are many variable factors that affect the growth and use of water by the plants, but present-day knowledge of them is limited. The water used by these plants probably represents the largest source of reclaimable water in the arid western United States. Although it appears feasible to salvage a part of this water, methods for doing so have not passed the experimental stage. In Nevada, it is estimated that it would be practical to salvage about 25 pct of the water wasted annually, or about 400,000 ac ft. This would be sufficient to irrigate about 133,000 acres of alfalfa having a crop value of $10,000,000.

(22) Seldon F. Cramer (South Pacific Div., Corps of Engineers, U. S. Army, San Francisco, Calif.) Activities of the South Pacific Division, Corps of Engineers, in Eradication and Control of Phreatophytes--As early as 1939, the Corps of Engineers provided funds to enable the U. S. Geological Survey to perform investigational work to determine the consumptive use of water by river-bottom growth in the Gila River Valley near Safford, Arizona. Since that time, the South Pacific Division of the Corps of Engineers has taken an active part in fostering other investigational work by fact-finding agencies on eradication and control of phreatophytes in southwestern United States. These activities culminated in the recent work of the Pacific Southwest Federal Inter-Agency Technical Committee, which recommended that a 77-mi flood channel, under study by the Corps of Engineers on Salt and Gila Rivers in Arizona, be used as a proving ground for self-financed cooperative studies by all interested State and Federal agencies.

(23) Curtis W. Bowser (U. S. Bureau of Reclamation, Denver, Colo.) Water Conservation through Elimination of Undesirable Phreatophyte Growth--A point now is being reached in our agricultural planning, especially in the Southwest, that all measures must be considered in extending the limited water supply. The removal of rank-growing riparian plants, or phreatophytes, which annually use enormous quantities of water in a non-beneficial manner, is one source of augmenting the existing supply. One of the most wasteful water users, and certainly a plant of limited value, is the salt cedar, a shrub which is not indigenous to this hemisphere. Clearing of certain salt-cedar infested areas would make available a greater amount of potential irrigation water, but such quantity would be less than the amount now being consumed non-beneficially because of continued evaporation and water use by replacement plants. Practically no consideration has been given to investigating in a comprehensive manner just how phreatophytes, and especially salt cedar, can be suppressed and what problems will be encountered following their removal from the river-bottom lands. The investigations with chemicals, particularly the phenoxyacetic acids, have indicated these compounds to be of certain value, with the possibility of their practical use over large areas to suppress salt-cedar growth. However, application of chemicals in all instances is not the answer to the problem. Other investigations such as mechanical clearing and the replacement of phreatophytes with economic plants using less water, or the channeling away of available subsurface water, thereby causing natural thinning of the existing plant cover, are only a few possibilities for consideration in an effort to control river-bottom vegetation for conservation of needed irrigation water. The landholders should assume the responsibility and desire for phreatophyte control. The action agency advocating phreatophyte eradication should not be bound forever to practice constant surveillance and periodic maintenance following a clearing program.

SECTION OF TECTONOPHYSICS

(1) Harry Jay Werner (Department of Geology, Johns Hopkins University, Baltimore, Md.) Preliminary Report on the Structural Geology of the Vesuvius Quadrangle, Virginia--Geologic

mapping of an area between Rockfish Gap and the James River of central Virginia is now in progress. The writer is mainly responsible for the mapping of the Vesuvius Quadrangle which lies mostly in the Blue Ridge physiographic province and includes portions of Augusta, Nelson, Rockbridge, and Amherst counties. The rocks range from early Pre-Cambrian to early Ordovician Age, but only early Cambrian (Chilhowee group) and the concordantly underlying greenstone and associated sedimentary rocks (Catoctin and Swift Run (or Oronoco) formations) of controversial age are discussed. These are the rocks which are involved in the complicated structures along the Blue Ridge. It is tentatively suggested that the volcanics in the basal Unicoi formation (lower Chilhowee) are the westward overlap of the Catoctin greenstone. Thus the stratigraphic position of the Catoctin and associated sediments may be correlated with those rocks of generally accepted Lower Cambrian Age. The following revised section is suggested:

Lower Cambrian
- Rome formation
- Shady dolomite
- Chilhowee group
  - Erwin quartzite
  - Hampton formation
  - Unicoi formation
    - Upper pebble quartzite member
    - Silstone and sandstone member
    - Volcanic member equivalent to Catoctin formation
    - Lower graywacke member equivalent to Swift Run or Oronoco formation

Unconformity ----------

Pre-Cambrian basement complex

The area is essentially an anticlinorium with its axis along the crest of the Blue Ridge. Superposed are anticlines and synclines of a second order and these in turn contain smaller and smaller folds. Some small, transverse folds occur with their axes normal to that of the major folds. The southeastern flank of the anticlinorium is cut by four thrust faults, none of which seems to show a large displacement. At least two of the thrust slices appear to be due to movement along the axial planes of the second-order anticlines. Fabric analyses, especially in the quartzites, indicate a high degree of grain orientation.

(2) Leo A. Herrmann (Department of Geology, Johns Hopkins University, Baltimore, Md.) The Structural Geology and Petrology of the Stone Mountain - Lithonia District, Georgia--The Stone Mountain - Lithonia District, Georgia, which occupies an area of approximately 100 sq mi, 15 mi east of Atlanta, Georgia, lies in the Piedmont physiographic province of the southern Appalachians. The metamorphic and igneous rocks of which the District is composed, have been deeply weathered to a red or brown saprolite, except for the more resistant bosses of gneiss and granodiorite. The chief rocks of the District include the Lithonia gneiss (migmatite), Norris Lake schist (mica schist and quartzite), and the Gneissic Complex, composed of interlayered biotite gneiss, amphibolite, biotite-hornblende gneiss, mica schist, and porphyroblastic biotite gneiss. The metamorphic series has been intruded by the Stone Mountain granodiorite and Mesozoic diabase dikes.

Deformation of the rocks of the District was accompanied by migmatization of, and the formation of flow folds and shear zones in, the Lithonia gneiss. The Norris Lake schist and Gneissic Complex were uplifted on the western flank of the Lithonia gneiss, and folded into broad, northwest trending folds. Previously formed transverse folds in the Norris Lake schist were refolded by the uplift. A very pronounced mica lineation was developed in the Lithonia gneiss, Norris Lake schist, and Gneissic Complex, parallel to minor, northwest trending fold axes. In addition, garnet porphyroblasts in the Norris Lake schist were elongated parallel to the mica lineation. The Stone Mountain granodiorite contains pronounced flow structures which include flow foliation (mica), mica fluctuation about an axis of rotation, and orientation of autoliths. The flow foliation is conformable to the discordant contact with the Gneissic Complex. The Lithonia gneiss was highly migmatized (and granitized) by concordant, syntectonic aplite veins which altered the rock into a biotite granite-gneiss. Relic bedding is found in the gneiss in the form of quartz-rich garnetiferous layers which are concordant with the gneissic banding. Drag folded layers in the gneiss may also be relic beds. Amphibolites form conformable layers (small and large) within the Norris Lake schist and Gneissic Complex. They have the composition of meladiorites, but show no evidence of an intrusive origin. They are considered to be either volcanic or sedimentary in origin.

The rocks of the District have been regionally metamorphosed to the level of the amphibolite facies. Two subfacies are distinguished; the sillimanite-almandine subfacies which is developed near the boundary of the Lithonia gneiss, and the staurolite-kyanite subfacies which is developed over the remainder of the District. The boundary between the two subfacies is marked by the change from epidote to diopside in the amphibolites.

(4) Judson L. Anderson (Department of Geology, Johns Hopkins University, Baltimore, Md.) Metamorphism in Howard and Montgomery Counties, Maryland--Geologic setting: The oldest rocks occur in the eastern part of the area and are known as the Baltimore gneiss. These gneisses form circular and elliptical domes and in one instance an elongated upfaulted mass. The circular dome in the northeastern part of Howard County has been pierced by the Woodstock granite. Overlying the Baltimore gneiss is the Setters quartzite followed in turn by the Cockeysville marble and the Wissahickon formation. The Wissahickon formation continues westward at least as far as the exposure of the Sykesville formation. A highly folded series of phyllites, quartzites, and conglomerates extend to the western boundaries of the counties. It is not known, at present, whether or not this series is equivalent to the Wissahickon formation. Conformable with the phyllites and quartzites and folded with them are relatively thin greenstones which may represent flows or sills. Larger dark intrusive bodies occur along the Potomac River. These are thought to be folded sills of meladiorite composition. Long narrow bodies of tonalite cut the country rock with discordant contacts. All rocks are cut by late granitic types of variable composition. Quartz veins, pegmatites, and small veins of epidote represent the last phase of igneous activity.

Metamorphism: The degree of metamorphism increases from west to east in the phyllites, quartzites, and schists. West of the Sykesville formation the schists contain large brown biotites. At the contact of the Sykesville, dark red garnets appear. This zone is from a half mile to a mile in width. Around the Baltimore gneiss domes, cyanite, garnet, and at times staurolite appear, indicating the highest degree of metamorphism in the schists. There is also an increasing in the anorthite content of the plagioclases from west to east. Locally, the schists have been metamorphosed by granitic intrusions and an aluminum silicate, probably sillimanite has formed. These sillimanites were altered by what is considered to be a late potash metasomatism which has changed them into a mass of muscovite slivers. In places, small granitic intrusions have apparently enlarged their contacts by soaking and incorporating the schistose country rock. A relict schistose texture is preserved and small garnets largely replace biotite. Late muscovite apparently representing a stage of potash metasomatism, largely replaces the biotites of the schists. The Sykesville formation, previously referred to as the Sykesville granite, represents another problem of metamorphism. In places, the rocks of this formation have the texture and mineral composition of a granite, but in others the texture is truly schistose. Inclusions of altered phyllitic material of varying sizes are common. Border facies suggest that the mass is intrusive. The internal character in many instances suggests a soaked schist similar to the Wissahickon. The body has the appearance of a migmatite.

(5) A. Nadai (Research Laboratories, Westinghouse Electric Corp., East Pittsburgh, Pa.) Stress and Strain in the Outer Solid Shell of the Earth--With comparatively simple means, expressions are developed for the distribution of the stresses and for both components of the displacements in radial and in tangential direction over extended portions in the thin solid shell of the Earth. The problem is solved for the distribution of stress and elastic strain in this thin solid spherical shell under the action of the tide generating forces of the Moon and Sun by making use of the theory of thin-curved elastic shells. The stresses and the cyclically changing components of the elastic displacements in tangential direction permitted to draw some conclusions concerning the permanent distortions to be expected in such a shell by considering the mechanical properties of the rocks under the high temperatures prevailing at the lower levels in the thin solid earth shell.

(6) J. Tuzo Wilson (Department of Physics, University of Toronto, Toronto, Ont., Canada) A Possible Explanation of Some Geophysical and Geological Observations According to the Contraction Hypothesis--According to the theory of failure of materials if a spherical shell with one point of weakness failed by sliding fracture this might be expected to produce a fracture shaped like a cone or sector of a cone having a surface pattern of circular or arcuate shape. In recent papers this idea has been coupled with Jeffreys' contraction hypothesis to suggest an explanation of the location and different directions of first motion of deep and shallow earthquakes and an explanation of the shape and some properties of the Mesozoic and Cenozoic belts of folded mountains and island arcs. In the present paper, this work is reviewed and extended and the features of young mountain belts more carefully analyzed. The same theory has been applied to some Paleozoic and Pre-Cambrian ranges in North America so as to try to indicate a possible mechanism for the growth of continental blocks during geological time. A preliminary attempt is made to estimate the quantities of the material involved, and the possible source and rates of deposition so as to see whether the theory is quantitatively tenable.

(7) W. S. Jardetzky (423 W. 118th St., New York, N. Y.) On the Problem of Atlantis--On assuming that the Mid-Atlantic Ridge is a "residual ridge" in the sense given by F. B. Taylor, an attempt is made to establish the conditions corresponding to the time, when the parts of the Earth's

crust could have been moved away from it on both sides. The general conditions of the sinking of a land connection between continents may be found, if the problem is posed in a simplified form. A closer approach to the real conditions is also suggested.

(8) John W. Graham and O. W. Torreson (Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, D. C.) Contrasting Magnetizations of Flat-Lying and Folded Paleozoic Sediments--The effort has been continued to trace the history of the Earth's magnetic field in geologic time by making determinations of the directions of permanent magnetism possessed by many sediments. These magnetizations apparently were acquired originally at the time of deposition and are retained faithfully for millions of years. Determinations on 170 rock samples taken from horizontal strata at 14 exposures of Ordovician through Permian age are contrasted with a comparable number of determinations on samples, chiefly of Silurian age, from folded Appalachian sections. The data from east and west flanks of anticlines differ from each other and differ from the observation in the flat-lying beds. These differences are attributed to deformation. Inverse magnetizations are present in the deformed geosynclinal sections but have not been found in contemporaneous flat-lying beds. It is believed that these anomalous magnetizations resulted from the physical and chemical conditions peculiar to the geosynclinal sections, and that they do not have any direct bearing on the past directions of the Earth's magnetic field. It is proposed that the Earth's field in North America has remained substantially constant for the past 400 million years.

AUTHOR INDEX

Aarons, J., 308, 321
Ackermann, W. C., 310
Adams, L. H., 307, 316
Ahrens, L. H., 306, 314
Albertson, M. L., 310
Anderson, J. L., 311, 335
Arnold, G. L., 308, 318
Ayres, J. C., 309, 324
Baker, L. S., 309, 321
Banks, R. E., 309, 323
Bascom, W. N., 309, 324
Black, H. F., 310, 330
Blaney, H. F., 311, 332
Bodman, G. B., 310
Bowser, C. W., 311, 333
Boyd, F. R., 310, 327
Bumpus, D. F., 309, 324
Burnight, T. R., 308, 320
Byrnes, B. C., 309, 321
Cain, J. C., 308, 319
Callaghan, E. C., 310
Chernosky, E. J., 309, 322
Clapp, P. F., 308, 319
Closs, K., 311
Cramer, S. R., 311, 333
Crary, A. P., 307, 316
Crays, A., 310, 329
Croft, A. R., 310, 311
Dehlinger, P., 307, 317
Dobrin, M. B., 307, 317
Dodd, P. H., 310, 328
Donley, D. E., 310
Donn, W. L., 307, 315
Ewing, M., 307, 314
Field, W. O., 310, 331
Fisher, J. E., 310, 331
Forrester, W. D., 307, 314
Gane, P. G., 307, 317
Garland, G. D., 307, 314
Garrels, R. M., 310, 328
Garstka, W. U., 310
Gebhardt, R. E., 309, 322
Gleeson, T. A., 308, 319
Goodell, B. C., 311, 331
Graham, J. W., 311, 336
Greenstone, R., 308, 321
Guenther, W. G., 308, 319
Gumbel, E. J., 310, 330
Hantush, M. S., 310, 330
Harrold, L. L., 310
Hastings, W. W., 310
Havens, R. J., 308, 320
Heinrich, E. W., 310, 328
Heiskanen, W., 307, 314
Herman, L., 308, 320
Herman, R., 308, 320
Hermann, L. A., 311, 334
Hess, S. L., 308, 319
Hinckley, T. J., 309, 322
Hitschfeld, W., 308, 318
Hough, J. L., 311
Howe, H. H., 309, 322
Huff, F. A., 310, 330
Hulburt, E. O., 308, 320
Hurley, P. M., 306, 308, 313, 320
Ives, R. L., 308, 318
Izzard, C. F., 311
Jacob, C. E., 310, 330
James, R., 309, 325
Jardetsky, W. S., 311, 335
Johnson, J. W., 309, 310
Johnson, M. H., 308, 320
Johnston, H. F., 309
Jones, C. L., 310, 328
Kaplan, L. D., 308, 319
Kats, S., 307, 316
Keller, F., Jr., 309, 321
Kennedy, G. C., 310, 327
Knapp, D. G., 309, 322
Koogler, J. T., 311, 332
Kooman, M. J., 308, 320
Krick, I. P., 310
Kulp, J. L., 306, 313
Langwell, P. A., 308, 318
Lawrence, P. L., 307, 317
Leipper, D. F., 309, 324
Long, R. W., 309, 322
Longard, J. R., 309, 323
Lowrey, R. D., 308, 319
Lynch, J., 307, 316
MacDougal, F., 309, 325
Malkus, J. S., 308, 319
Marble, J. P., 306
McCall, J. S., 307
McCrady, E., 308, 313
Medina, M., 307, 314
Miller, A. R., 309, 323
Moore, R. C., 306, 313
Morison, J. R., 309
Munk, W. H., 309, 323
Nadai, A., 311, 335
Nelson, M. G., 310
O'Dea, P. L., 309, 322
O'Donnell, G., 308
O'Halloran, D. J., 307, 315
O'Keefe, J. A., 307
Oliver, J., 307, 316
Packer, D. M., 308, 320
Peterson, H. V., 310
Pierson, W. J., Jr., 309, 325
Poland, J. F., 311
Press, F., 307, 316
Price, W. A., 309, 323
Puertas, C. G., 309, 323
Rappleye, H. S., 307, 315
Rauch, S. E., 309, 325
Redfield, A. C., 309, 324
Roberts, E. B., 309, 322
Roberts, F. H. H., Jr., 306, 313
Robinson, T. W., 311, 333
Schell, I. I., 309, 324
Schwarz, H. E., 311, 332
Scolnik, R., 308, 320
Skibitzke, H. E., 311, 332
Skilliman, T. L., 309, 323
Simon, R. F., 307, 317
Speert, J. L., 307, 314
Spreen, W. C., 308, 318
Stern, M. E., 308, 319
Stout, G. E., 310, 330
Swain, F. E., 310, 329
Swingle, D. M., 308, 321
Tatel, H. E., 307, 316
Taylor, A. B., 311, 332
Thomas, C. W., 309, 323
Torreson, O. W., 311, 336
Tuve, M. A., 307, 316
Turner, S. F., 311, 332
Upham, S. H., 309, 324
van Bavel, C. H. M., 310, 331
Verhoogen, J., 310, 328
von Arx, W. S., 309, 324
von Schelling, H., 310, 329
Waltner, A. W., 310, 331
Weiss, L. L., 308, 318
Weiss, O., 309, 321
Wells, H. W., 308, 320
Werner, H. J., 311, 333
Wilcox, R. E., 310, 327
Williams, H., 310, 326
Wilm, H. G., 310
Wilson, J. T., 311, 335
Wilson, W. S., 308, 319
Woollard, G. P., 307, 315
Work, R. A., 310
Worzel, J. L., 307, 314
Wyatt, W. H., 308, 318
Yogi, K., 310, 326
Yoder, H. S., 310, 327
Zies, E. G., 310, 325

Program for 1951
American Geophysical Union,
1530 P Street, Northwest,
Washington 5, D. C.

TRANSACTIONS
AMERICAN GEOPHYSICAL UNION

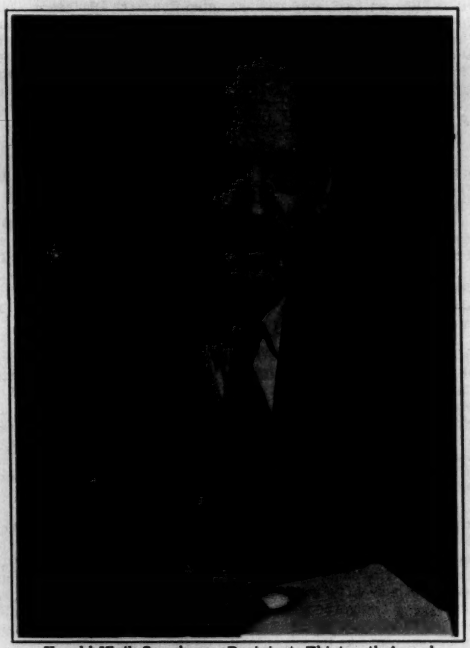
Volume 32 JUNE 1951 Number 3

THIRTEENTH AWARD OF THE WILLIAM BOWIE MEDAL

CITATION

Prepared and presented by Richard H. Fleming

Mr. President: The Committee on the Award of the William Bowie Medal is proud to recommend the bestowal of this award on Harald Ulrik Sverdrup, Director of the Norwegian Polar Institute.



Harald Ulrik Sverdrup - Recipient, Thirteenth Award
William Bowie Medal - April 30, 1951

Some know Dr. Sverdrup as an oceanographer and acknowledge him as the world's outstanding expert on the physical aspects of the ocean waters. Others recognize him as an authority on the complex problems of the interaction of the sea and atmosphere and think of him as an investigator in meteorology, the discipline in which he received his training and in which he has maintained a lively and productive interest. To others he is an adventurous explorer who spent some six years on board Roald Amundsen's ship Maud, frozen in the Polar Pack, and who accompanied the Wilkins-Ellsworth North Polar Expedition aboard the submarine Nautilus. Still others recog-

nize his original contributions to terrestrial magnetism and electricity on which he published extensively as an outcome of his work on the Maud. It would indeed be difficult, if not impossible, to find anywhere in the world a man whose interests and great abilities cover so many of the fields that are represented in the American Geophysical Union.

As a young man, Dr. Sverdrup was an assistant to Prof. V. Bjerknes. During this period he published a series of theoretical and analytical papers involving the application of hydrodynamics to meteorology and oceanography. His outstanding paper was his doctoral thesis which presented the first consistent picture of the dynamic and thermodynamic structure of the North Atlantic trade winds. After some six years at a desk, Sverdrup welcomed the opportunity to accompany Captain Amundsen as chief scientist on the Maud expedition. The published results of the field work conducted during the period 1918-1925 comprise more than fifty papers dealing with the geophysics of the Arctic. These original contributions represent a very large fraction of our factual knowledge of the region.

After his return to Norway in 1925, Dr. Sverdrup occupied the chair of Meteorology at the Geophysical Institute, Bergen, and later was appointed Research Professor at the Christian Michelsen Institute. While primarily concerned with the analysis of the Maud data, and with editing the reports of other specialists, he found time to assist the Department of Terrestrial Magnetism of the Carnegie Institution of Washington in the analysis of the oceanographic material collected on the last cruise of the non-magnetic vessel Carnegie. He also participated on the Nautilus expedition and accompanied Dr. H. W. Ahlman during a study of the high-lying snow fields on Spitzbergen. Ever willing to assist others, he reported, for example, on data collected by the British Discovery Committee in the Antarctic and on material obtained by the British-Australian-New Zealand Antarctic Research Expedition.

As a recognized authority on oceanography, meteorology, glaciology, and magnetism and with wide experience in field work and research, Dr. Sverdrup was, in 1936, invited to accept the position of Director of the Scripps Institution of Oceanography of the University of California. His twelve-year tenure of this position further broadened his interests to include all phases of oceanography and revealed his talents as an administrator and teacher. In 1948 he returned to Norway to take charge of the newly-created Norwegian Polar Institute. A contributing factor in his decision to return to Norway was the hope that he could foster international cooperation in geophysical research. One result of these efforts is the joint Norwegian, Swedish, and British expedition to the Antarctic that is conducting a program of glaciology and related studies. Dr. Sverdrup spent the past southern summer with the expedition.

Dr. Sverdrup's publications range from theoretical papers on vectors to popular items on natural history and ethnology. His greatest accomplishments are in the analysis and synthesis of complex field data which he treats with clarity and simplicity. His theoretical contributions have almost always evolved from such field investigations. Among his outstanding accomplishments in geophysical research are his work on the trade-wind systems, his study on the dynamics of the tides where the rotation of the Earth and bottom friction are taken into account, studies on the growth and behavior of surface waves, and his rational explanation of the influence of the winds on the major current systems. It would be an omission to neglect his contributions to "The Oceans," published in 1942, that clearly show his mastery of the seas.

One of the stipulations for the award of the William Bowie Medal is that the recipient must have made outstanding contributions to the advancement of cooperative research in geophysics. Dr. Sverdrup's interests are always towards cooperation--with his co-workers, between institutions, and among nations. That these relationships have been both stimulating and productive can be seen in a list of 164 papers published prior to 1948. The more valuable aspect of cooperation is, however, his interest in bringing together the techniques and scientists of different fields to attack the borderland areas between the classic fields of geophysics. Such an approach is extremely productive in sciences as young as those that make up Geophysics.

The Committee on the Award of the William Bowie Medal is proud to nominate Harald Ulrik Sverdrup for the award of the William Bowie Medal. By this means the American Geophysical Union recognizes his great contributions to science, conveys the warm greetings of his friends, and wishes him continuing happiness and achievement.

In closing, the Committee wished to have it made a matter of record that their selection of Dr. Sverdrup was unanimous and that there was not a single oceanographer on the Committee!

PRESENTATION BY PRESIDENT WALTER H. BUCHER

May I ask Dr. Christophersen, Cultural Attaché of the Norwegian Embassy, to step forward?

The special qualities which we emphasize are recorded on the medal, in the words "Unselfish Cooperation in Research." Those of us who have the privilege of knowing Dr. Sverdrup personally look up to him for the unswerving, self-sacrificing, "unselfish" devotion he brings to the great tasks he supports and the straightforward approach, simple honesty, and human understanding which are essential for leadership in cooperative enterprises. It is indeed a great honor and pleasure to entrust to you this medal for transmittal to Dr. Sverdrup with the best wishes and cordial greetings of the geophysicists of the American Geophysical Union.

RESPONSE BY ERLING CHRISTOPHERSEN

Mr. President: In the absence of Dr. Sverdrup, I have the great honor to be present on his behalf on this very notable occasion. At the same time, I feel that I am not only representing Dr. Sverdrup, but also his country of birth--Norway. I know that Dr. Sverdrup feels that the honor you are bestowing upon him today is a recognition of cooperation not only within the field of geophysics, but also across national borders. On his behalf, and also on behalf of Norway, I am proud and deeply honored to accept the William Bowie Medal. I telegraphed Dr. Sverdrup asking him for instructions on what to say today, and he has informed me that he will write a letter of response for your records.

However, off the record, I would like to say that when Dr. Sverdrup came through Washington on his return from Scripps Institution to take over his new position as Director of the Norwegian Polar Institute, we had lunch together at the Cosmos Club. He then told me of his deep gratitude towards your country and the people with whom he had worked here, and asked my advice on how he--when he got back to Norway--could do something in return for what he had received here. Fortunately I had some good advice for him--at least I thought it good advice--namely, to take over my Summer School for American Students at the University of Oslo. This he did, and the enthusiasm and energy with which he has discharged his duties in this respect is proof that he was deeply honest and sincere in his desire to reciprocate. This new token of esteem which you have bestowed upon him today, will, I am sure, stimulate him to work even harder for cooperation in research and thereby better understanding, which is the basic philosophy behind the William Bowie award.

I also yield to the temptation--with your permission, Mr. President--to take advantage of this occasion to extend a personal thanks to Dr. Fleming for his wonderful response to my appeal for cooperation between his office and the Antarctic Oceanographic Expedition which I was planning when I came to this country in 1947. This is another proof of the readiness with which the members of your organization, Mr. President, are willing to take the consequences of the high ideals which have been set for the work of the American Geophysical Union, under the motto of "Unselfish Cooperation in Research."

ACCEPTANCE BY HARALD U. SVERDRUP

When I read the citation prepared by my friend, Dr. Richard H. Fleming, I felt that had I been present in person to receive the William Bowie Medal I should have been very embarrassed. There is, however, one point which Dr. Fleming barely touched and which I should like to emphasize, namely, that friends and organizations in the United States have given me ample opportunities to develop my interests.

The reason why Professor V. Bjerknes was able to offer assistantships to a series of young, eager students, including myself, was that for many years he had a grant from the Carnegie Institution of Washington. It is a curious fact that during the four and one-half years Bjerknes spent in Leipzig, from January 1913 to August 1917, his two Norwegian assistants were indirectly paid by the Carnegie Institution, even after the United States had entered the first World War.

My contact with the Carnegie Institution became closer when in 1918 the Department of Terrestrial Magnetism placed instruments for magnetic and atmospheric-electric observations at the disposal of Roald Amundsen's Maud expedition and subsequently gave me opportunity to discuss the results. Later on, the Woods Hole Oceanographic Institution cooperated in the oceanographic work of the Nautilus expedition. Finally, when the University of California appointed me Director of the Scripps Institution of Oceanography, I was placed in a position with outstanding possibilities for development of oceanographic research.

During my early visits to the United States and my years at the University of California, it was my privilege to become closely associated with the American Geophysical Union and to follow its impressive expansion during the last 30 years. If I have been able to contribute somewhat to the activities of the Union, I consider this only as a small repayment because of the opportunities offered me.

During my entire career I have benefited from cooperation between organizations and countries, I have learned to realize the importance of working together, and I have tried to do my share. Therefore, I know of no honor I appreciate more than the award of the William Bowie Medal because it is given me in recognition of efforts toward cooperation. I take this opportunity to express my most sincere gratitude to the American Geophysical Union and to my many friends among its members.

THE WILLIAM BOWIE MEDAL

The William Bowie Medal was established by deed of gift in 1939 in honor of the distinguished and beloved geodesist and geophysicist whose name and likeness it bears. It is awarded annually in the name of the American Geophysical Union for distinguished attainment and outstanding contribution to the advancement of cooperative research in fundamental geophysics. The William Bowie Medalists, with the dates of their awards, are:

William Bowie (deceased)	1939
Arthur Louis Day	1940
John Adam Fleming	1941
Nicholas Hunter Heck	1942
Oscar Edward Meinzer (deceased)	1943
Henry Bryant Bigelow	1944
Jakob Aall Bonnevie Bjerknes	1945
Reginald Alsworth Daly	1946
Felix Andries Vening Meinesz	1947
James Bernard Macelwane	1948
Walter Davis Lambert	1949
Leason Heberling Adams	1950
Harald Ulrik Sverdrup	1951

Transactions, American Geophysical Union Volume 32, Number 3 June 1951

THE APPLICATION OF ELECTRICAL COUNTING TO THE COMPILATION OF FREQUENCY DISTRIBUTIONS AND CORRELATION TABLES

A. R. Kassander, Jr. and D. W. Stebbins

Abstract--An electrical-mechanical tabulator is described which presents statistical data in array form immediately on the conclusion of a test, thereby eliminating the time-consuming process of measuring and transferring data from tape records. The basis of operation is to cause differential relays to direct a sampling pulse to appropriate counters representing different class intervals of the variable being examined. Thus the number of counts in each counter is proportional to the length of time that the variable was in a particular class interval. In its present form, the instrument is capable of presenting a nine class frequency distribution for one variable, a twenty-five cell correlation diagram for two variables, or six tetrachoric correlation diagrams for four variables.

Introduction--Frequently a research project becomes almost impractical because so much time and labor must be budgeted to the task of extracting large quantities of data from a continuous record and tabulating them in a form suitable for statistical computations. This is especially true in the field of meteorology where data are conventionally recorded photographically, or more commonly, on one of the commercial pen recorders. The experimentalist is then faced with the task of measuring, point by point, the tape record and transferring these data to tables for computational purposes.

The Iowa State College geophysical group recently undertook an investigation which required the knowledge of the standard deviations of static and dynamic pressure fluctuations in the atmosphere and the coefficient of correlation between them. It was decided that time could be well spent in the design of a simple tabulating device that would deliver the data in array form upon

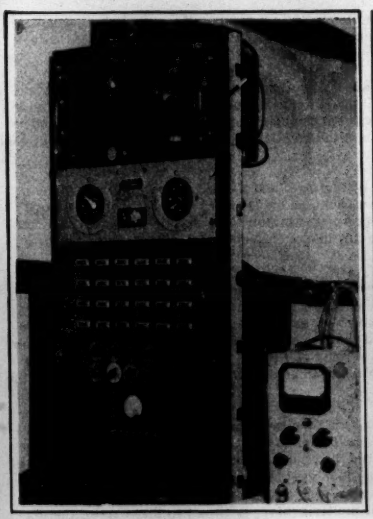


Fig. 1--Front view of tabulator

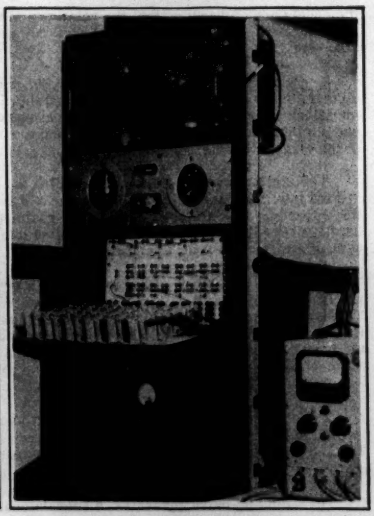


Fig. 2--Tabulator with patch panel exposed

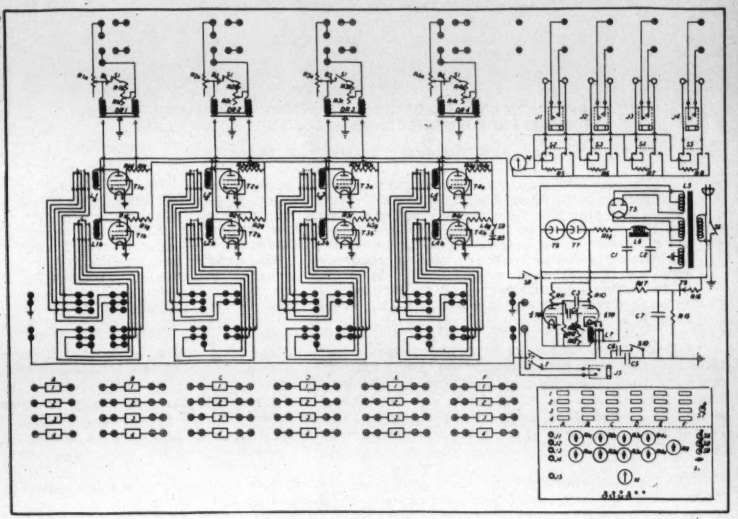


Fig. 3--Schematic diagram of tabulator

the conclusion of a test so that the relatively simple statistical computations could be immediately performed. The results obtained certainly warranted the effort spent in constructing the instrument.

Instrumentation--The tabulator (see Fig. 1 and 2) consists of three basic parts: the signal divider, the sampling pulse generator, and the counters. The sequence of operations is to divide into class intervals the incoming electrical signal representing the variable to be investigated, to sample this variable at a uniform rate, and to count the number of times that the signal lay in each of the class intervals.

The circuitry will be described with the aid of Figure 3 and Table 1. The signal or signals are fed into the system through one or more of the phone jacks J1, J2, J3, or J4. The resistors R5, R6, R7, and R8 are each equal to the resistance of the meter M so that by means of switches S2, S3, S4, or S5 the meter can be connected into any one of the inputs for monitoring purposes without altering the input impedance.

The signal is divided into class intervals by means of the differential relays DR1, DR2, DR3, and DR4. Resistors R1a, R2a, R3a, and R4a are used to vary the limits of the class intervals. The battery, switch, and other resistors associated with each differential relay provide a centering adjustment for the relay. The R-a series and the R-c series of resistors are controlled from the front of the panel as shown in the lower right corner of Figure 3. The unconnected tip jacks adjacent to the differential relay jacks are for patching in series or shunt resistors to provide the required input impedance for the signal.

The counters required more current for operation than the differential relays could carry. Hence the latter were used to trigger the thyratrons T-a and T-b. The thyratrons controlled the L-a and L-b series of relays which in turn actuated the counters shown as rectangles in the lower portion of Figure 3. Hence the T-a, T-b, and L-a, L-b combinations represent current amplifiers.

The sampling pulse generator, a conventional multivibrator, is shown in that part of the diagram associated with T8. The repetition frequency of the sampling pulse is controlled by R9 and can be varied from one per second to ten per second. The multivibrator controls relay L7.

Table 1--Specifications for components in the recorder

R1a = R2a = R3a = R4a = 25,000-ohm variable resistor
R1b = R2b = R3b = R4b = 22,000-ohm fixed resistor
R1c = R2c = R3c = R4c = 100,000-ohm variable resistor
R1d = R1f = R2d = R2f = R3d = R3f = R4d = R4f = 10,000-ohm fixed resistor
R1e = R1g = R2e = R2g = R3e = R3g = R4e = R4g = 1-megohm fixed resistor
R5 = R6 = R7 = R8 = Meter resistance
R9 = 50,000-ohm variable resistor
R10 = R11 = 18,000-ohm fixed resistor
R12 = 68,000-ohm fixed resistor
R13 = 6,700-ohm fixed resistor
R14 = 6,000-ohm fixed resistor
R15 = 25,000-ohm fixed resistor
R16 = 2,400-ohm fixed resistor
R17 = 50-ohm fixed resistor
C1 = C2 = 8-mfd condenser
C3 = C4 = 2-mfd condenser
C5 = 14-mfd condenser
C6 = 4.5-mfd condenser
C7 = 40-mfd condenser
DR1 = DR2 = DR3 = DR4 = Weston MR-5 differential relay modified to be centered at 0 volt
L1a = L1b = L2a = L2b = L3a = L3b = L4a = L4b = Guardian, series 200, 110VAC DPDT relay
L5 = Power transformer: 115V input; 600VCT, 5VCT, 6.3V output
L6 = 16h filter choke
L7 = Western Electric D168479 mercury contact relay
T1a = T1b = T2a = T2b = T3a = T3b = T4a = T4b = type 2051 thyratron
T5 = type 83
T6 = T7 = type VR 150
T8 = type 12 AU7
T9 = Selenium rectifier
B1 = B2 = B3 = B4 = 3-volt dry cell
B5 = 22 1/2-volt dry cell
M = 300-0-300 microammeter
A1, B1, etc. = Harco 110VAC solenoid counter

The first model of the tabulator used 115 VAC to activate the counters when L7 closed. This was thought to be the simplest procedure, but proved unsound because the sampling pulse had a finite duration of time. The result was that if the input signal was varying rapidly, two different relays might close in succession during one of the closures of L7, thus causing two counters to record the same pulse. This is equivalent to the situation that might arise when preparing a histogram and entering a borderline sample into both classes on either side of the border. This, of course, is statistically unsound, and tends to bias that portion of the range in which the population is varying most rapidly.

This situation was remedied by the use of a source of energy sufficient to fire only one counter to record one event. The solution of the problem is shown in that portion of the schematic diagram involving the condensers C5 and C6. The selenium rectifier, T9, and C7, R15, R16, and R17 provide a simple source of DC voltage. During the interval between pulses, condenser C5 is charged through the normally closed contact of the relay L7. Then, when the relay closes to the other pole for the sampling pulse, C5 discharges through the appropriate counter to record a count. The magnitude of C5 is adjusted so that it will store only enough energy to fire one counter Then, if, within the duration of a pulse, contact is made to a second counter, it will not count until the next pulse. The sampling period is begun and ended with switch S7.

The phone jack, J5, and its associated tip jacks are used, so that external information, such as timing pulses from another source may be provided on the control panel.

In order to facilitate adjustment of the tabulator and to check its operation, an "input simulator" was constructed according to the schematic diagram of Figure 4. It is simply a device to provide a variable voltage in the range desired to set the magnitude of the signals for which the differential relays will close. As illustrated in Figure 4, two independently controlled outputs are provided so that the operation of the counters, as well as the range settings, may be checked in correlation studies.

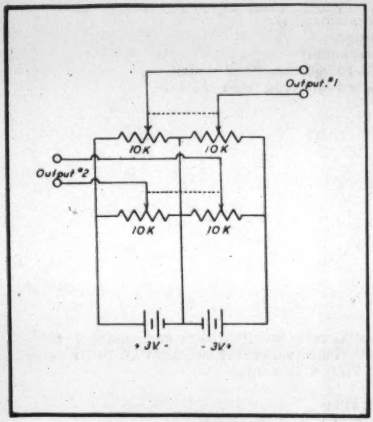


Fig. 4--Input simulator

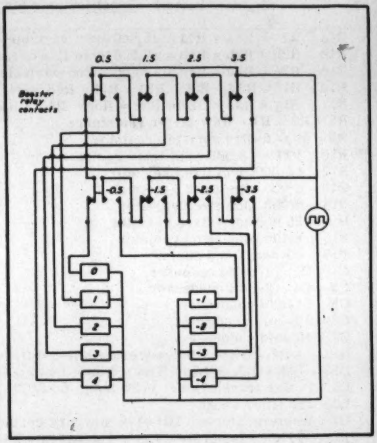


Fig. 5--Wiring scheme for frequency distribution

Frequency distribution for one input signal--In the description of the operation of the tabulator, reference will be made only to the booster relay contacts, since their action is identical with the differential relay action.

For the frequency distribution, the differential relays are all connected in parallel with the pair of input terminals. Either of the outputs of the simulator is connected to the signal input of the tabulator. The magnitude of the output is adjusted to the desired level of the first-class interval boundary using the meter M connected across the input as the indicator. The appropriate resistor R-a is adjusted until the associated differential relay will just close as the simulator output level is increased very slightly.

The magnitude of the output is next adjusted to the desired level of the second-class interval boundary and the second resistor R-a is adjusted until its associated differential relay will just close as the simulator output is increased very slightly. This same procedure is then repeated for each class interval boundary.

Using the four differential relays it is thus possible to provide nine class intervals: a center one in which the signal will not operate any of the relays but the sampling pulse will fire a particular counter; one on either side of this one for which the signals come through the differential relay that closes first; and others on either side of these with signals coming from the progressively "stiffer" relays. The outermost class intervals are unbounded on the outside.

Figure 5 shows the wiring arrangement for a nine-class histogram. The figures opposite the relays represent the class interval boundaries in class interval units, and those in the counters represent the means of the classes in class interval units. The sample pulse is represented by the square wave depicted in the figure. Note that the normally closed contacts are utilized so that the counters can count only when the signal is in the zone they represent, whereas the relays, of course, successively close and remain closed as the signal increases. If the signal had a value of +3 class interval units, for example, the relays below 0.5, 1.5, and 2.5 would have the contacts closed that are now shown as open but the pulse would go through counter 3 only. If it were desirable to obtain a cumulative curve rather than a frequency distribution, this could be done by simply connecting all of the relay armature contacts directly to the sample pulse rather than by obtaining the sample pulse through the normally closed contact of the next higher relay. Note also that the zero zone counts may be obtained by requiring that both of the normally closed contacts of the +0.5 and -0.5 booster relays are closed.

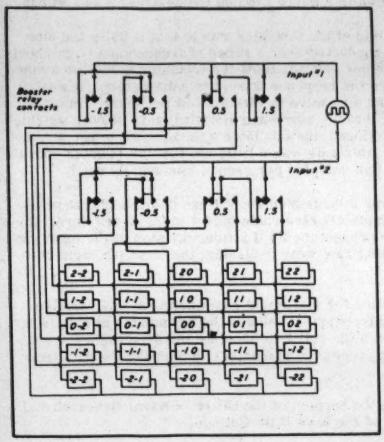


Fig. 6--Wiring scheme for correlation diagram

Correlation table for two input signals--The correlation coefficient to be used is the Pearson product-moment coefficient. For this system the two input signals are each divided into five classes. In order to calculate the correlation coefficient, the frequencies of the twenty-five possible combinations are required. Figure 6 shows the wiring scheme to accomplish this.

Two differential relays are connected in parallel with one input signal, and the other two differential relays are connected in parallel with the second input signal. The class interval boundaries of the two different variables are then set by means of the range control resistors in the same manner as before with the input simulator. The pulses of the sampling generator are then recorded in the appropriate cell. This operation requires 25 counters. An additional one was added to the counter panel after the picture of Figure 1 was taken.

In Figure 6, in addition to the path through the proper counter, alternate paths exist for the pulse through other counters. However, the combination of these alternate paths has roughly twice the resistance of the proper counter path, and the maximum current through any "improper" counter will be one-half of the current through the proper counter. Thus, by choosing the correct amount of capacitance in the sampling pulse energy source, it can be arranged that just enough current will pass to fire the proper counter but not enough to fire any other. The switch, S10, adds additional capacitance to the pulse energy source when 25 counters are used. The additional energy is required since more alternate paths are present than when only nine counters are used and hence a smaller fraction of the total energy goes through the recording counter.

Other applications--The tabulator will perform equally well for any type of signal which can be converted into an electrical signal. Existing tape records can be analyzed by having an operator follow the trace with a stylus which is rigidly connected to the sliding contact of a slide wire potentiometer. The voltage between one end of the potentiometer and the sliding contact can then be made proportional to the magnitude of the deflection of the trace on the tape. This voltage then becomes the signal for the tabulator. Correlation could also be performed between two tapes by having them driven together at their appropriate relative speeds and having two operators tracing records. Similarly, autocorrelation techniques could be devised wherein the two styli are placed a given distance apart on the same tape record.

If it were desired to tabulate a series of numbers rather than continuous data, the problem could be solved by having an input simulator set up similar to the one described previously and having the dials calibrated in terms of the magnitude of the variable being analyzed. 115 VAC could then be introduced by means of J5, and this voltage could be used through the system rather than the sampling pulse. The 115 VAC could be controlled by a key, and each setting of the input simulator could then be recorded by a closing of the key. Two signals would work equally well for correlation studies.

The tabulator can also be used for tetrachoric correlation between two of four input signals. In this method, one differential relay serves each of the input signals.

After the tabulator was completed and in use, an instrument was reported [GERHARDT, 1950] whose basic function was similar to the one described in this paper. In place of the counters and master sampling pulse system this instrument used electric clocks, thereby introducing into the system the lag time to start the clocks. It was suggested by the author that the method could be used for correlation studies if an N^2 array of clocks were set up. It was quite satisfying to note that the two chief objections to this most recently reported tabulator had been satisfactorily met in the tabulator described herein. These objections were the relatively high lag error introduced

by the clocks, and the fact that if the instrument were extended to perform correlation tabulations it could become "unwieldy and overly complicated in a hurry" to use the designer's own words.

Performance--The first step after completion of the tabulator was to test it using the sine wave output of a signal generator. Tests were conducted over a range of frequencies from about 1.5 cycles per second to one-thirtieth of a cycle per second, using the tabulator wired for a nine-class histogram. Over this range of frequencies the response was quite satisfactory. It was possible to estimate the standard deviation of the sine wave to within a few per cent. This was considered an extreme test, because of the fact that the sine wave distribution is heavily weighted at the extremes of the distribution. As was mentioned, the tabulator was designed to use a sampling rate of ten samples per second. However, this rate was a little too fast for reliable operation of the particular counters used. A rate of five samples per second was usually used.

This tabulator worked very successfully over a large number of tests of atmospheric pressure fluctuations. It is hoped to construct a completely electronic model in the near future. No difficulty would be encountered in expanding the present model if a finer division of the input signals were desired. Similarly, if a faster sampling rate were desirable, the counters could be supplemented with electronic scalers.

The tabulating technique has a wide application for statistical examination of any variable that can be reduced to an electrical signal. The technique combines the advantages of relatively small lag error, compactness, and versatility with the ability to tabulate the data as they are accumulated, thus eliminating the time-consuming process of manually transferring the data from conventional tape records.

Acknowledgment--The authors acknowledge the support of the Office of Naval Research and the cooperation of the Physics Department staff of the Iowa State College.

Reference

GERHARDT, J. R., A simple integrating device for the routine statistical analysis of recorded data, Trans. Amer. Geophys. Union, v. 31, pp. 183-186, 1950.

Physics Department,
Iowa State College,
Ames, Iowa

(Communicated manuscript received January 15, 1951;
open for formal discussion until November 1, 1951.)

Transactions, American Geophysical Union Volume 32, Number 3 June 1951

RAINFALL FREQUENCY: AN ASPECT OF CLIMATIC VARIATION

Luna B. Leopold

Abstract--Analyses which have been made in the past have shown no significant trend in annual values of rainfall during the period of rainfall records in the southwestern United States. In the present study, frequency of daily rains of various sizes are analyzed for four long-record stations in New Mexico. It is shown that the frequency of rains smaller than 0.50 inch in a day progressively increased from 1850 to about 1930. Opposite trends in different size classes tended to partially compensate one another in such a way that trends do not appear in the annual rainfall totals. Frequency of rains of various sizes comprising wet years and dry are compared. Some effects of changes in rainfall frequency on vegetation and erosion are discussed.

During the period since the last retreat of the glaciers of Wisconsin time, climatic variations have caused important changes in the regimen of rivers, particularly in western United States. Over a large area, both ephemeral and perennial streams have, by alternate aggradation and degradation, built a series of terraces made up of relatively fine-grained material. Because changes in climate operate on streams through the medium of induced changes in rainfall and through concomitant changes in vegetal cover, it is a problem of considerable interest to workers in the field of sedimentation to attempt to particularize the nature of these climatic variations and their effects on the flow of streams.

Since the advent of heavy grazing on the semi-arid lands of western United States, an epicycle of erosion has begun. It is clear that overuse of these lands by stock has been a major factor in initiating this erosion. But in view of the geologic evidence that climatic variations in the post-glacial but prehistoric period had similarly caused successive periods of erosion alternating with sedimentation, some geologists have argued that the modern erosion is a result of a slight shift of climate, and that grazing acted as a trigger-pull, timing a change about to take place.

In considering the question of the relative importance of overgrazing versus climatic change in causing the modern epicycle of erosion in the southwestern United States (hereafter called the Southwest), two of the key points at issue are: (1) Is there in the Southwest any evidence of important climatic variations in the past century which might have some bearing on the cause or timing of the epicycle of erosion? (2) In what direction must the climate change be in order to initiate erosion? That is, will a change toward a more arid regime initiate erosion or will it cause alluviation? The present study deals with these two points.

There is voluminous evidence of significant climatic variations in the past century in large areas over the world [as examples, see LYSGAARD, 1949; AHLMANN, 1948]. However, it has been recognized by THORNTHWAITE, SHARPE, and DOSCH [1942] and other authors that the annual values of precipitation and temperature for the Southwest do not show significant trends. On the basis of the lack of progressive variation, it has been argued by them that climatic change cannot be considered an important contributing factor in the present epicycle of erosion.

Climatic variations have been studied by use of data on a wide variety of phenomena. Not only have records of various meteorologic elements been analyzed, but indirect evidence of great value has been derived from archeology, dendrochronology, pollen analysis, and other fields. In the use of precipitation data for studies of climatic variation there has been a tendency to restrict analyses to the consideration of average values, primarily mean annual values. Mean annual values of precipitation are useful in reducing voluminous observations to a form simple enough for easy handling, but it should be remembered that annual values of precipitation may obscure short-period features in the rainfall pattern which in themselves might have great significance.

Climatic variations are made up of various combinations of wet and dry years. Wet and dry years must differ not only in total annual precipitation but also in the frequency of daily rains of various sizes, and changes in rainfall frequency may have as important effects on vegetation as changes in annual totals.

In the present study the longest precipitation records in New Mexico were analyzed to deter-

mine whether there is evidence of secular trends in the frequency of daily rains of different sizes. Wet years are compared with dry years with respect to rainfall frequency and frequencies are compared between stations of different average annual precipitation.

Trends in annual number of rains--The number of cases of rains of different magnitudes was tabulated from the records of daily rains published by the U. S. Weather Bureau in Climatological Data and Monthly Weather Review for years subsequent to 1895. For the period 1849-1895 the daily rainfall data are not published and were tabulated from the original records kept by the Surgeon General and Army Signal Corps, available in the Archives of the United States, Washington, D. C. For the first portion of the present analysis, the breakdown by sizes of rains consisted of three categories, 0.01-0.49 inch, 0.50-0.99 inch, and ≥1.00 inch in a day. Traces of rain were not considered. In cases of very old records the number of traces was used as an indication of whether or not the observer was actually reading the gage in months when the number of cases of measurable rain seemed unusually low. The observers of the Surgeon General's Office and of the Army Signal Corps were generally more assiduous in writing useful explanatory notes than were the observers of more recent years.

In New Mexico, the records shown in Table 1 were considered sufficiently long to be useful in investigating trends in frequencies.

Table 1--New Mexican records used in investigating trends

Station	Elevation	Mean annual rainfall	Location in State
	ft	in	
Santa Fe	7010	14.3	North central
Fort Union	6880	18.0	Northeastern
Albuquerque	5200	8.1	Central
Las Cruces (Agri. College)	3860	8.6	South central

Santa Fe records from 1849 to 1892 were taken at Fort Marcy, located on a low bench overlooking the city, close to the later gage location. The Albuquerque gage apparently has always been located on the plateau overlooking the river valley. For many years it was at the University about two miles from its present location but in a nearly identical topographic position.

The early portion of the record for Las Cruces Agricultural College is made up of data from Fort Seldon, 17 miles upstream and somewhat closer to the river, and Fort Filmore, four miles down the river and in topographic position similar to that of the College.

San Marcial appears in "Climatic Summary of the United States" as a long record but in fact is made up of a combination of Fort Conrad, Fort Craig, San Marcial, and Socorro. A study of the record led to the conclusion that it is too heterogeneous for the present purpose.

The number of cases per year for each of the three rainfall size classes as well as the annual rainfall totals are plotted as five-year moving averages in Figure 1. The lack of any trend in the annual totals is obvious, and is borne out by statistical comparison of the means of the first half versus the last half of the records.

On the other hand, the trend exhibited in the frequency of the small rains, 0.01-0.49 inch, is striking. The small rains generally increased in number from the beginning to the latter part of the record at all stations. For Albuquerque and Las Cruces, the upward trend continued at least until 1940, while Santa Fe shows a decrease from about 1933 to 1945.

The trends in rainfall frequency represent one aspect of climatic variation. In determining whether such trends in hydrologic data result from real physical changes in climatic factors, they might logically be judged by two criteria. First, the data showing the trend should, in successive time units, be mutually independent and be arranged in a non-random manner. If the individual observations partake of some natural cycle (for example, annual cycle) causing a repetitive variation of values, the observations should be grouped in time units such that the cyclic variation is eliminated.

The second criterion is that the trend should be of such magnitude that important physical effects on land or people are implied. In instances where these criteria are fulfilled, neither

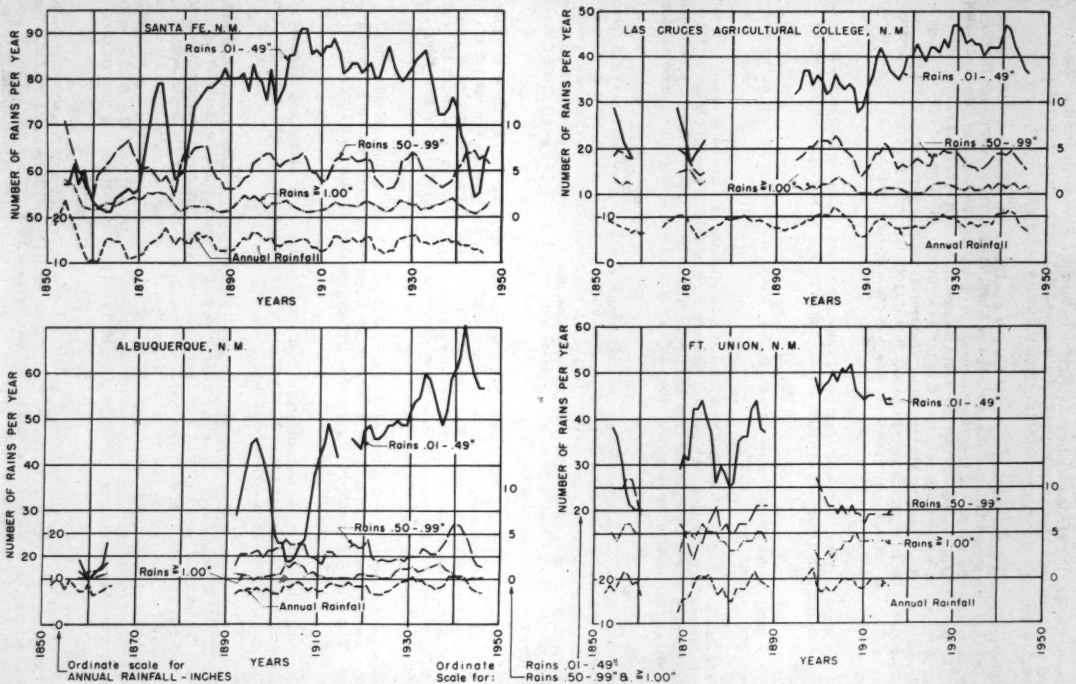


Fig. 1--Frequency of rains of various amounts in a day at four long-record stations in New Mexico, five-year moving averages (five-year moving averages of annual rainfall are presented for comparison)

permanent changes nor cyclic variations in climatic factors are necessarily implied. Such trends are generally not useful for prognostication, but the establishment of their reality is a step in understanding the types of variations to which climatic factors are subject.

With regard to the first criterion, it is of interest to examine the Santa Fe record between 1850 and 1939. This period of record was studied by THORNTHWAITE, SHARPE, and DOSCH [1942]. In view of the absence of progressive change in the annual rainfall totals, they concluded that "the more or less random interactions of air masses ... determine present climatic variations" in the Southwest. We will split the record into two parts, 1849-1895 and 1896-1939, approximately the division used by Thornthwaite. The average number per year of rains of 0.01-0.49 inch in the first part of the record was 66 and in the later part 81, with a standard deviation of 3.0. The difference between these means is statistically significant well beyond the one per cent level.

In the same periods, the average number of rains per year in excess of 1.00 inch was 1.7 and 1.1 respectively, with a standard deviation of 0.3. The difference is significant at the five per cent level.

The number of rains of intermediate size, 0.50-0.99 inch, was not significantly different between the two periods.

For another test of the trend, a simple form of sequential analysis can be applied. An upward trend in the sequence of values will provide a tendency for long runs of numbers less than the median followed by long runs greater than the median [HOEL, 1947, p. 177]. Thus, a pronounced trend will be characterized by long runs, whereas a weak trend will have a large number of short runs.

Consider the Santa Fe record for which nearly complete data are available from 1853-1949. The median number of rains per year in the category 0.01-0.49 inch is 76. In this period the sequence is broken by missing years in 1862, 1866, 1867, 1882, and 1883. Assuming the magnitudes of frequencies for the missing years in the most adverse manner, that is, to provide the maximum number of runs, there would be 38 runs. The probability is 0.01 that such a small number of runs would occur in a random sample.

The frequency of rains of 0.01-0.49 inch at Albuquerque (1889-1948) was subjected to a similar test of the number of runs. The missing years, 1891, 1915, and 1916 are similarly interpolated in the most adverse manner. The probability is 0.05 that such a small number of runs would occur in a random sample. In the Las Cruces record (1886-1948), the probability is more than 0.05 and therefore the number of runs could occur in a random sample. The Fort Union record is too broken to provide a satisfactory test.

Because the annual rainfall totals do not show the trend apparent in rainfall frequencies, there is implied a compensation by which the increase in number of small rains is balanced by a concurrent decrease in number of large rains, a fact already demonstrated in the statistical test of the mean frequencies for Santa Fe.

It appears, therefore, that the rainfall-frequency data for the few available long records in New Mexico show trends which are real and are not merely the result of random variations. Thus the first criterion mentioned earlier is fulfilled.

Trends in seasonal rainfall frequencies--Figure 2 shows the march of number of small rains (0.01-0.49 inch) at Santa Fe, New Mexico, broken down into its summer and non-summer components. Both seasons show the trend in rainfall frequency though it is somewhat more pronounced in the non-summer data. The summer rainfall is derived primarily from moisture brought in at high levels from the Gulf of Mexico under the influence of the anticyclonic circulation of the upper-air counterpart of the Bermuda anticyclone. Winter rain is primarily caused by the passage of fronts or upper troughs precipitating moisture derived from Pacific sources. The specific weather features of the lowest troposphere are quite different in the two seasons, yet both seasons partake of a similar trend.

Within this overall similarity in trend, the rainfall frequencies of the two seasons may be in or out of phase for periods of a few years. Note that the summer rainfall frequency was high and winter frequency low in the period 1853-1863 and vice versa in 1864-1871. A similar out-of-phase relation exists in the period 1895-1905. In-phase relation is apparent in 1870-1880 and approximately so in 1937-1947.

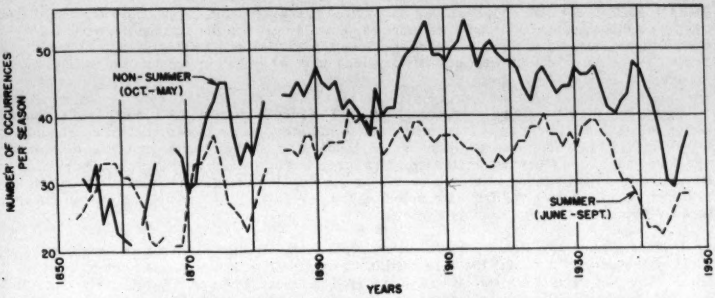


Fig. 2--Seasonal frequency of rainfalls of 0.01-0.49 inch in a day, five-year moving averages, Santa Fe, New Mexico

It is suggested, therefore, that the short-period variations tend to be random and are different in nature from the longer period secular trends which are probably governed by the large features of the general circulation. The secular trends are doubtless related to the same factors which have caused the climatic variations now well authenticated for many areas in the northern hemisphere.

Rainfall frequency in relation to erosion history--It is logical to assume that rainfall frequency has a substantial effect on the erosion process. Small rains, that is, rains of small amount in a day, do not contribute greatly to erosion because they generally produce only small surface discharges, if any. The smallest rains tend only to wet the soil and thus are utilized by plants or evaporated from the soil surface. Large rains tend to penetrate to a deeper layer of soil and thus contribute also to plant growth, but a much larger percentage of the water from a large rain runs off. Erosion, both sheet and gully, is caused primarily by the large rains.

The seasonal occurrence of rains of various magnitude provides some indication of the effects of frequency on plant growth. Table 2 shows that the four summer months contain more than half of the cases of rains of all sizes, and an even larger share of the heavy rains. Note that the mean intensity of the small sizes of rains is greater in summer than winter.

Thus, a decrease of the small rains of summer which provide the main moisture for grasses, particularly annual grasses, would weaken that portion of the protective vegetation. Both shrubs and perennial grasses depend greatly on late winter moisture infiltrating deeply in the soil. A decrease in small rains in winter would also adversely affect the vegetal cover.

In summary, it seems clear that during the early portion of the past hundred years, New Mexico experienced a relatively low frequency of small rains both in summer and winter. At least in some areas, the early period of record shows a relatively high frequency of large rains. Such a circumstance must have been conducive to a weak vegetal cover and relatively great incidence of erosion. That the modern epicycle of erosion began in the Southwest about 1885 is well established

Table 2--Frequency of rains of various sizes and their contribution to the annual total, Las Cruces, New Mexico, 1892-1939

Rainfall size classes	Summer, June-Sep.		Non-summer, Oct.-May	
	Number per year	Per cent of total annual rain	Number per year	Per cent of total annual rain
in				
0.01-0.09	10.4	6	10.0	4
0.10-0.49	9.3	29	8.2	16
0.50-0.99	2.6	23	1.4	8
≥ 1.00	0.5	12	0.2	2
All sizes	22.8	70	19.8	30

[BRYAN, 1925, 1928]. We see, then, that not only was grazing tending to promote erosion at that time, but meteorologic conditions were more conducive to erosion than during the period of the present generation. Thus there is established concrete evidence of a climatic factor operating at the time of initiation of southwestern erosion which no doubt helped to promote the initiation of that erosion.

The association of arid climate with erosion--The second question to be discussed is the direction in which a climate must change in order to initiate a period of degradation of alluvial valleys. The field evidence strongly favors the association of aridity with periods of erosion. Sand dunes have been found associated with stratigraphic evidence of degradation in many localities which have been studied. These associations have not been confined to a single area but, on the contrary, have been found from the Hopi Country of Arizona to the western border of the High Plains of Texas, and north as far as Wyoming.

The occurrence of caliche is typical in the upper strata of alluvial formations which were eroded subsequent to or during the accumulation of the caliche. The occurrence of strong calcification in the B horizon of a fossil soil is interpreted as direct evidence of a relatively arid climate [BRYAN, 1948]. It is possible, of course, that the period of formation of the caliche in the fossil soil was neither contemporaneous with nor associated with the subsequent erosion of the formation, but in the typical case there is no evidence to dispute the association of the erosion of the alluvium with the semi-arid climate which produced its caliche subsoil.

Tremendous herbivorous animals such as the mammoth could hardly have lived in any area where the vegetation was sparse. Since these animals became extinct during a period of great erosion at the end of Deposition 1 of the Southwestern Alluvial Chronology [BRYAN and McCANN, 1943], we have further inference that aridity was associated with erosion.

It is the purpose of this section to investigate the nature of wet and dry years with respect to rainfall frequency and to draw from the results, inferences regarding the effects of relative wetness on the erosion process.

Frequency characteristics of stations of different annual precipitation--Las Cruces and Santa Fe, New Mexico, were chosen to represent in a rough way a low-elevation dry area in New Mexico and a higher relatively moist one. Santa Fe has a mean annual precipitation more than 1.5 times that of Las Cruces. It is desirable to determine what sizes of daily rainfalls provide Santa Fe with a higher annual mean than that of Las Cruces.

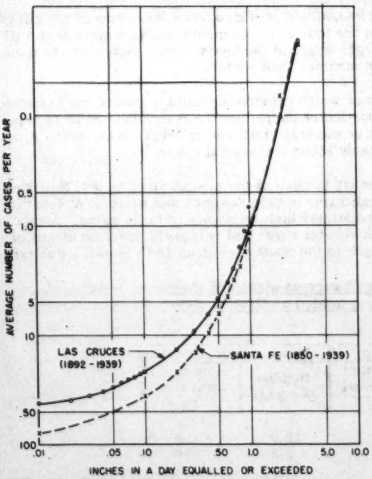


Fig. 3--Cumulative frequency curve of daily rains of various sizes, Las Cruces and Santa Fe, New Mexico

The numbers of days having various rainfall amounts were counted or tallied at the two stations. The class intervals were 0.01 inch between 0.01 and 0.09, 0.1 inch between 0.10 and 0.99 inch, and one inch for rains equal to one inch or more. The number of cases in each class interval was divided by the number of years of record to obtain the average annual frequency of rains of a given size. In Figure 3, accumulated frequency of rains is plotted against size classes of daily amount of rainfall.

Several important relations are apparent from this graph. Las Cruces gets only 60 per cent of the mean annual rainfall of Santa Fe, yet the frequency with which the two stations receive large rains (greater than one inch in a day) is about the same. The difference in the total annual rainfall is made up by the larger number of small rains experienced by Santa Fe.

In New Mexico the mean annual rainfall of a given station is higher than that of another station because of a larger number of rains, and more especially of small rains. A corollary to this fact is that at a given station, a large percentage of its total annual fall is contributed by the small rains, as will now be demonstrated.

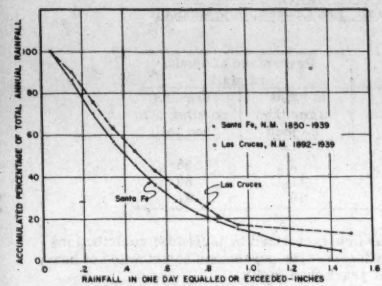


Fig. 4--Contribution of daily rainfalls of various sizes to annual total rainfall

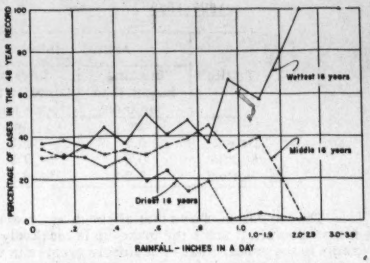


Fig. 5--Percentage of cases of daily rains of various sizes contributed by the driest, wettest, and near-normal years, Las Cruces, New Mexico, 1892-1939

Using the data in the frequency histograms of daily rainfall at the two stations, the mean value of each class interval of rainfall was multiplied by the respective number of cases. The resulting numbers provide an approximation of the total contribution of the daily rains of various sizes. Dividing the total for each size class by the total rainfall for the station and then accumulating, we obtain the accumulated percentage contribution of each size class to the total. These percentages are plotted against the daily rainfall size classes in Figure 4 which shows that because the number of cases increases exponentially with decreasing values of daily rainfall, the smaller rains contribute a large percentage of the total annual fall.

Rains smaller than 0.42 inch in a day contribute 50 pct of the annual total at Santa Fe. Rains smaller than 0.48 inch contribute 50 pct of the Las Cruces total. Note that rains in excess of 1.5 inches in a day make up 13 pct of the Las Cruces annual total, but only five per cent of the Santa Fe annual rainfall.

Frequency of daily rainfall amounts in wet and dry years--Now that we have some idea of the frequency relationships at stations of different annual precipitation, let us determine how wet years and dry years at a given station contribute to the mean annual precipitation. For this purpose the 48 yearly rainfall totals for Las Cruces in the period 1892-1939 were arranged in order of magnitude. The array was then divided into three equal groups or tritiles. Thus the frequency of each size class of daily rainfall for the wettest tritile can be compared with that of the middle and driest tritiles. The number of occurrences in each size class were counted for each of the tritiles separately.

For a given size class, the frequency in percentage of the total number of cases in the 48-year record was computed for each third part and plotted in Figure 5. The figure shows that the dry years contain (1) the smallest total number of rainfall days, (2) none of the days of highest daily rainfalls, and (3) a progressively decreasing share of cases as one goes from low to high rainfall categories.

The middle tritile contained nearly the same percentage of the total cases in all size classes except that it contained none of the daily rains greater than two inches. All the latter were included in the wet or upper tritile.

In the case of the Las Cruces record, the average annual rainfall for the 16 wettest years (upper third) was 11.6 inches, for the middle third 8.4 inches, and for the driest third 5.8 inches, so the wettest third of the years had a mean annual rainfall about twice that of the driest third.

Now it is obvious that the concentration of the heavy rains in the wet third increased the annual totals of the respective years in which they occurred, and therefore helped determine which years would fall in the upper or wet third. The extent to which the heavy rains contributed to the total rainfall of each third is summarized in Table 3.

Table 3--Contribution of rains less than and greater than one inch in a day, to the total annual rainfall, Las Cruces, New Mexico, 1892-1939

Tritile	Annual rainfall		Percentage of annual rainfall	
	In rains larger than one inch	In rains smaller than one inch	In rains larger than one inch	In rains smaller than one inch
	in	in		
Driest	0.1	5.5	2	98
Middle	0.9	7.5	11	89
Wettest	2.2	9.4	19	81

The tabulation shows that although wet years are characterized by increased contributions from rains of all sizes the make-up is markedly different. The percentage contribution of heavy rains to the annual total is decidedly greater in wet years than in dry.

Meteorologically this relation means that a greater frequency of weather conditions from which rain is liable to fall differentiates wet years from dry ones. As a result of increased frequency of such synoptic conditions, all sizes of rainfalls are increased in number.

Seasonal rainfall--We shall now examine the number of occurrences of rains of different sizes by season, again using Las Cruces as an example. Table 4 shows the average number of cases of various sizes of daily rains per season, summer (June-September) separated from non-summer (October-May), and keeping the division by thirds based on annual totals. It is immediately apparent that all the cases of rains greater than two inches in a day occurred in the summers of wet years. The summers of wet years constitute a total of 64 months of record. These experienced more rains greater than one-inch, a total of 25, than the remaining 512 months of the record which experienced 15.

Table 4--Number of cases per season of daily rains of various sizes, Las Cruces, New Mexico, 1892-1939, subdivided by tritiles of annual rain, and by season

Rainfall size classes	Summer, June-Sep.			Non-summer, Oct.-May		
	Dry	Middle	Wet	Dry	Middle	Wet
in						
<0.09	8.4	11.9	12.0	9.8	9.9	10.1
0.10-0.49	8.7	10.9	10.5	7.0	8.2	9.4
0.50-0.99	1.3	2.9	3.6	0.7	1.4	2.1
1.0 -1.9	0.6	0.38	0.81	0	0.31	0.19
2.0 -2.9	0	0	0.25	0	0	0
3.0 -3.9	0	0	0.06	0	0	0

Relation of rain frequency to annual rainfall--The effect of doubling the annual rainfall will now be investigated. The annual totals for the 48 years of record (1892-1939) at Las Cruces were again arranged in order of magnitude and divided into 12 parts, each containing four years. No division into seasons was made. For each of the four-year periods, the average numbers of cases of daily rains were plotted against the respective size categories. The sum of the products of number of cases times the weighted average of the respective sizes should equal the annual rainfall total for the given part. The curves drawn through the points were adjusted until this equality existed. From the family of curves so constructed, the data for Figure 6 were compiled, in which the relation of annual rainfall to the frequency of rains of various sizes is shown. In the family of curves of Figure 6, any abscissa value is equal to the sum of the products of number of cases times weighted mean rainfall in the various size classes.

It is now possible to compute the effect of a doubling of the annual rainfall. Since the mean annual rainfall at Las Cruces is 8.5 inches, let us note the effect of a hypothetical change of annual rainfall from a value of six inches to a value of 12 inches.

Inspection of Figure 6 indicates that for a fixed relation between the frequencies of different class intervals of rainfall, a doubled annual rain would be composed of less than twice the number

Table 5--Average frequency per year of rains of various sizes in four segments of the record, 1850-1948

Station	Period	Size classes of daily rains, inches			Mean annual rain for period
		0.01-0.49	0.50-0.99	>1.00	
					in
Santa Fe	1850-1880	59.7	5.7	1.96	14.6
	1881-1910	80.8	5.5	1.07	14.4
	1911-1930	82.8	5.3	1.20	14.3
	1931-1948	71.5	5.1	1.05	12.9
Las Cruces	1850-1880[a]	23.8	3.8	1.65	7.9
	1881-1910[a]	31.7	4.7	1.17	8.8
	1911-1930	41.1	3.9	0.50	8.4
	1931-1948	42.0	3.3	0.67	8.6
Albuquerque	1859-1880[a]	21.2	1.3	0.40	8.0
	1881-1910[a]	30.5	2.9	0.71	7.7
	1911-1930	47.0	2.6	0.56	8.5
	1931-1948	58.3	3.4	0.67	9.0

[a]Record broken, as explained in connection with Figure 1.

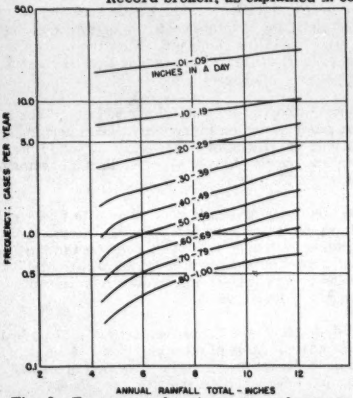


Fig. 6--Frequency of various sizes of rains in relation to annual rainfall total, Las Cruces, New Mexico, 1892-1939

of small rains and more than twice the number of moderate rains. The number of rains in the highest category studied, 0.80-1.00 inch, was exactly doubled. This can also be seen in the varying slope of the family of curves. The data are insufficient, however, to establish definitely whether these characteristics are significant.

On the other hand, the trend in rainfall frequencies shown in the graphs of Figure 1 indicates that during the period of record, the relation between frequencies changed. The records for the period 1850-1948 for Santa Fe, Las Cruces, and Albuquerque were arbitrarily divided into four periods broken at 1880, 1910, and 1930. The average numbers of rains in the size categories by periods are shown in Table 5.

It can be seen that in this sequence of years the relation between numbers of different sizes of rainfall shifted. The important thing to note is that in the later parts of the hundred-year record the frequency distribution at Las Cruces became more like that of Santa Fe even without a change in the annual totals. For example, if the frequencies at Las Cruces in the period 1931-1948 (42.0, 3.3, 0.67) are multiplied by the ratio of the annual rain at Santa Fe to Las Cruces for the period (12.9/8.6 = 1.50), they become 63.0, 5.0, 1.00, approximating the figures for Santa Fe for the same period. In the period 1850-1880, however, a similar adjustment (14.6/7.9 = 1.13) makes the frequencies 26.9, 4.3, 1.87, much lower than for Santa Fe in the low rainfall category but nearly equal in the high category.

It can be concluded, therefore, that during periods when there is no differential trend in rainfall frequencies, an increase in annual rainfall implies a disproportionate increase in frequency of rains of moderate size, 0.40-0.70 inch in a day, relative to the increase in frequency of the lightest and heaviest rains. It can be presumed that the largest rains are those most effective in erosion. What size of rains are most effective in promoting vegetation is not known in detail. To the extent that the rains of moderate size are the most important for promoting vegetation, Las Cruces data indicate that an increase in annual rainfall at the station tends to promote vegetation more than erosion.

On the other hand, in view of the fact that, during the period of record of the stations studied, the changes in annual rainfall totals have had no trend while the relation of frequencies of different sizes of rains has changed markedly, it seems logical to assume that the latter effect is more important in the erosion process than are the secular changes in annual rainfall totals.

Discussion of the results--It has been shown that secular variations in the frequency of rainfall occur in the precipitation records at the few long-record stations in New Mexico. Statistical analysis shows that these variations are not due to chance. The fact that all the available long records show similar trends indicates that the trends are probably regional in their geographical effect and points to shifts in the general circulation as the probable cause.

The rainfall record provides no indication of the magnitude or even the nature of changes in the general circulation required to produce the observed trends in rainfall frequency, but the analysis of the few stations reported here shows that trends in frequency affected both winter and summer precipitation. It is possible that a slight shift in the average position of zones of convergence related to high-level pressure troughs might influence the average amount of precipitation falling during each potentially rain-producing synoptic situation. In this manner the frequency of each size-class of rainfall might be altered.

The importance of the observed trends in rainfall frequency lies less in an improved understanding of the relation of the general circulation to climatic variation than in the introduction of another manner in which climatic variations affect the physiographic forces operating on the Earth's surface. It has long been known that records of many rivers in the United States show breaks or inconsistencies in the relation of total precipitation to total runoff. In many cases these breaks are due to local factors such as change in exposure of the rain gage. When the breaks in the rainfall-runoff relations are not random or due to local causes, it is possible that they result from changes in the frequency of rains of various sizes.

Many rivers in the semi-arid portion of western United States exhibit a series of terraces developed during alternating periods of aggradation and degradation in the post-glacial period. Changes in the rainfall-runoff relations, as the cause of variations in runoff regimen, would in many respects provide a more logical explanation of the observed river terraces than a hypothesis based only on changes in average annual precipitation.

Total sediment movement past a given point on a river is generally correlated with total stream runoff. General observations of many western rivers indicate that periods of flood or of relatively high water discharge are periods during which sediment previously deposited in the valleys of trunk streams tends to be scoured out and moved downstream. Periods of high discharge, in other words, tend toward degradation of the river channel. Accumulation or aggradation of the river bed seems to take place during periods of low flow.

Low and high flows both occur during any period of years, and the net tendency of a river bed to aggrade or degrade must depend on the relative number of flows of different sizes. Thus it seems that the change of river action from alluviation to degradation is less a function of annual precipitation than of the frequencies of various sizes of rains which presumably are closely correlated with the frequency of various sizes of flow in streams.

These relations delineate what is possibly an important way in which climatic variations operate to produce physiographic changes in rivers, particularly in semi-arid areas.

Acknowledgments--The writer gratefully acknowledges the many valuable suggestions made by Walter B. Langbein and Thomas Maddock, Jr. during the course of the study. C. F. Brooks and the late Kirk Bryan of Harvard University kindly read an early draft of the manuscript. Ethel Wilson was of material aid in tabulating data from records in the United States Archives.

References

AHLMANN, H. W., The present climatic fluctuations, Geogr. J., v. 112, pp. 165-195, 1948.

BRYAN, KIRK, Date of channel trenching (arroyo cutting) in the arid Southwest, Science, v. 62, pp. 338-344, 1925.

BRYAN KIRK, Change in plant associations by change in ground water level, Ecology, v. 9, pp. 474-478, 1928.

BRYAN, KIRK, Los suelos complejos y fósiles de la altiplanicie de Mexico, en relación a los cambios climáticos, Bol. Soc. Geol. Mexicana, v. 13, pp. 1-20, 1948.

BRYAN, KIRK, and F. T. McCANN, Sand dunes and alluvium near Grants, New Mexico, Amer. Antiquity, v. 8, pp. 281-295, 1943.
HOEL, P. G., Introduction to mathematical statistics, John Wiley and Sons, 258 pp., 1947.
LYSGAARD, LEO, Recent climatic fluctuations, Folia Geographical Danica, Copenhagen, v. 5, 94 pp., 1949.
THORNTHWAITE, C. W., C. F. S. SHARPE, and E. F. DOSCH, Climate and accelerated erosion in the arid and semi-arid Southwest, with special reference to the Polacca Wash drainage basin, Arizona, U. S. Dept. Agri. Tech. Bull. 808, 134 pp., 1942.

U. S. Geological Survey,
Washington, D. C.

(Communicated manuscript received December 14, 1950;
open for formal discussion until November 1, 1951.)

Transactions, American Geophysical Union Volume 32, Number 3 June 1951

A GRAVITY RECONNAISSANCE OF THE ISLAND OF OAHU

George Prior Woollard

Abstract--A network of 30 gravimeter stations was established on the island of Oahu in the fall of 1948. A study of these gravity data in conjunction with those of the U. S. Coast and Geodetic Survey on the island and the observations of Vening Meinesz in the adjacent deep-sea areas indicates the following: (1) The mean specific gravity of the island block down to the ocean floor is 2.3. (2) The regional Bouguer anomaly values corrected for the mass differential of the sea water and island lavas at the sea stations show an anomaly of -75 mgals on the island. (3) Of this deficiency in attraction, part may be related to a thinning of the crystalline crustal layer because of the withdrawal of magmatic material at depth to furnish the lavas and a possible magma chamber at depth. (4) The balance of the anomaly presumably is related to surface subsidence whereby lavas and sediments of 2.3 specific gravity are brought into juxtaposition with oceanic crustal material of 2.95 specific gravity. (5) Regional subsidence of the island to date on the above basis has amounted to between 8,000 and 10,600 ft. (6) To achieve isostatic equilibrium (remove the +50 mgals regional isostatic anomaly) an additional subsidence of approximately 7,000 ft will be required. (7) Local anomalies of (+) 110 mgals occur over the ancient Koolau and Waianae volcanic vents, but no appreciable anomaly is found to be associated with the more recent volcanic vents as Diamond Head, Koko, the Punch Bowl, or Salt Lake. The explanation of this phenomenon appears to lie in the difference in the relative sizes of the early and late vents and the difference in the petrology of the throat material present and its density contrast with the surrounding volcanic flow material. (8) Computations as to the depth to which a maximum density contrast of 0.6 gm/cc exists between volcanic throat material and flow material to satisfy the 110 mgals anomaly indicate subsidence to a depth of 9,000 ft below the ocean floor. This value is in general agreement with the subsidence determined from the analysis of the regional anomalies (8,000 to 10,600 ft). (9) Since it is improbable that the early lavas were vesicular, these figures on degree of subsidence probably represent minimum values. (10) None of the classical mechanisms for achieving isostatic equilibrium under the Airy and Pratt theories of isostasy appear valid for this type of geologic structure.

Introduction--The existence of pronounced gravity anomalies on the island of Oahu has been known for some time. Seven pendulum gravity stations established by the U. S. COAST AND GEODETIC SURVEY [1930] showed a change of 91 mgals in the isostatic anomaly on the island. The trans-Pacific gravity traverse established by VENING MEINESZ [1934], which crosses the Hawaiian Swell at Oahu, showed a change of 40 mgals in the isostatic anomaly between the deep-sea stations and the island station established at Honolulu. Recent observations by the writer [WOOLLARD, 1950] on Oahu, and observations in the adjacent deep-sea areas by C. L. Drake of Columbia University (described in personal communication, 1950), verify these earlier findings and show that the regional isostatic anomaly for the island mass is about +50 mgals and that there are local superimposed anomalies of approximately 100 mgals.

The significance of the gravity field on Oahu has been studied previously by several investigators. In 1924, C. H. Swick [DUERKSEN, 1943] calculated that the density of Oahu was 3.34 gm/cc on the assumption that the positive isostatic anomalies resulted from extra mass in the island blocks and not lack of compensation. GORANSON [1928] concluded that the island was essentially uncompensated and, although not composed of abnormally heavy rocks, did constitute a sinking load on the sub-Pacific crust. In 1930, H. C. Mitchell [DUERKSEN, 1943] concluded that the surface density of the island was abnormally high and that complete isostatic compensation did not exist. VENING MEINESZ [1941] showed that the regional isostatic anomalies in large measure could be removed by assuming regional compensation spread out uniformly to a distance of 232 km. Furthermore, the assumption of abnormally high density values (2.937 gm/cc) would also aid in reducing the anomalies. DALY [1942] concluded that the island represents an excess mass upon the Earth's crust. DUERKSEN [1943] concluded that if the density of island mass is about that of average crustal material (2.67 gm/cc), then the island constitutes an extra load that is only partially compensated. Much of the anomaly, however, could be removed by increasing the density of the compensation block by 0.0505 gm/cc. GUNN [1943] showed quantitatively that the observed regional Free Air anomaly pattern on and adjacent to the Hawaiian Islands is to be expected with a strong lithosphere overlying a weak asthenosphere under conditions of isobaric

Table 1--Comparison of data secured at reoccupied gravity stations on Oahu

Location	Old value	Authority	New value	Authority
	gal		gal	
Honolulu	978.951	USC and GS	978.943	Woollard
Honolulu Port	978.941	Vening Meinesz	978.941	Woollard
Niu Long. Sta.	978.952	USC and GS	978.953	Woollard
Waianae (15)	979.034	USC and GS	979.031	Woollard
Waianae (16)	979.033	USC and GS	979.030	Woollard
Pearl Harbor	978.938	Drake	978.937	Woollard

Table 2--Principal facts of gravimeter stations on Oahu

Station	Latitude	Longitude	Elevation	Observed gravity	Bouguer anomaly
	° ′	° ′	ft	gal	gal
1	21 19.2	157 55.15	6	978.9266	+0.1969
2	21 20.35	157 57.50	21	978.9316	+0.2016
5	21 16.80	157 47.15	38	978.9533	+0.2279
6	21 17.15	157 44.10	12	978.9534	+0.2260
7	21 18.45	157 39.55	72	978.9531	+0.2280
8	21 20.60	157 42.40	13	978.9956	+0.2649
9	21 23.10	157 45.50	125	979.0356	+0.3091
10	21 25.95	157 44.60	10	979.0412	+0.3049
11	21 22.20	157 47.65	1,190	978.9215	+0.2598
12	21 20.55	157 50.20	400	978.9553	+0.2478
13	21 21.60	157 56.70	6	978.9368	+0.2047
14	21 23.85	157 59.50	100	978.9458	+0.2070
15	21 22.55	158 02.80	173	978.9616	+0.2385
16	21 20.25	158 05.50	81	978.9814	+0.2551
17	21 23.00	158 08.75	17	979.0122	+0.2795
20	21 28.00	158 09.00	280	979.0336	+0.3113
21	21 26.85	158 00.95	600	978.9295	+0.2275
22	21 32.60	158 02.55	1,051	978.9028	+0.2222
23	21 35.05	158 06.40	18	978.9629	+0.2176
24	21 39.15	158 03.80	27	978.9517	+0.2028
25	21 41.75	158 01.40	12	978.9607	+0.2083
26	21 39.30	157 55.60	6	978.9688	+0.2186
27	21 36.65	157 54.65	6	978.9790	+0.2314
28	21 34.75	157 53.15	6	978.9854	+0.2399
29	21 29.20	157 50.85	8	979.0173	+0.2775
30	21 26.50	157 48.95	40	979.0311	+0.2959

equilibrium. He also showed that for reasonable assumptions regarding the Earth's crustal strength and thickness there is a crustal deformation of about 14,000 ft beneath the Hawaiian Islands.

The present investigation differs from these previous ones in that (a) it is based upon a more comprehensive group of gravity data, (b) it is divided into separate analyses of the regional and local gravity anomalies, and (c) it is based primarily upon a study of the Bouguer anomalies.

Gravity network on Oahu--The writer added 26 gravity stations to the existing network of seven stations on the island of Oahu in the summer of 1948 using a high-range Worden gravity meter. Comparative data for the older stations reoccupied are listed in Table 1, and the principal facts for the new stations established are given in Table 2. The combined groups of observations give a network of gravity stations at about four-mile intervals along the main highways circling and crossing the island.

As any adequate interpretation of gravity data must take into consideration local geologic factors, a brief resume of the physical geography and geology of the island of Oahu will be presented before examining the gravity data.

Physical geography and geology of the Hawaiian Swell--The Hawaiian Islands lie near the southeastern end of a submarine mountain range (the Hawaiian Swell) which is over 1,600 mi long.

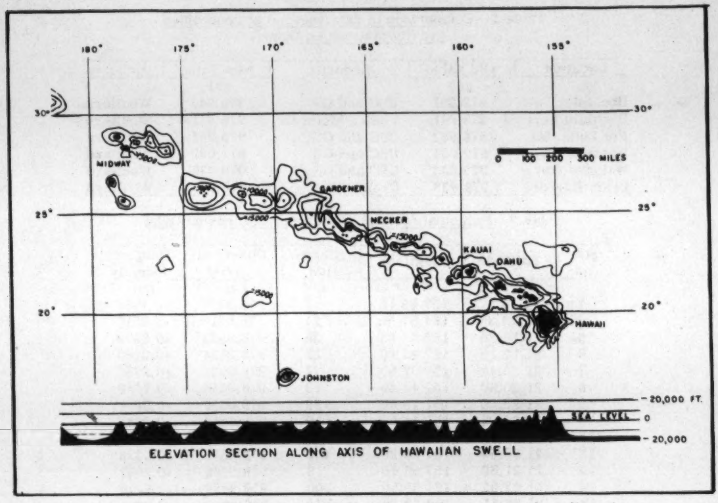


Fig. 1--Location of Hawaiian Swell and elevation section along its axis

This range is about 130 mi wide at its base and rises from a mean depth of 15,000 ft below sea level to sea level at the northwest end and to several thousand feet above sea level on the island of Hawaii at the southeast end. Most of the peaks on this range outside of the Hawaiian Island group appear only as atolls. The Hawaiian Islands consist of a group of volcanic islands most of which are now quiescent. The exceptions are on the island of Hawaii, the most southeasterly member of the group at the terminus of the mountain range. The general location and extent of the Hawaiian Swell is shown in Figure 1.

BETZ and HESS [1942] have postulated that this submarine mountain range originated as a series of lava outpourings from a fissure system in the ocean floor. Methods of origin that have been postulated for this fissure system are: (1) a tensional crack on the axis of a crustal fold; (2) a simple tensional fracture in the ocean floor; (3) a group of enechelon fractures developed by a horizontal shearing couple; and (4) a strike slip fault.

STEARNS [1946], referring to the observable loci of lava eruptions in the Hawaiian Islands, notes that the lava rose along tension cracks bounding lozenge-shaped blocks strung out linearly from southeast to northwest with vents spaced at about 25-mi intervals. This pattern is suggestive of a series of enechelon fractures. The presence of a pronounced depression paralleling the swell on its north side, however, may be interpreted as evidence of a crustal fold or a fault structure.

Since the northwest end of the Hawaiian Swell is marked exclusively by atolls, and evidence of active volcanism in recent time is only found at the southeast end, it would appear that (a) the northwest end of the range is older than the southeast end, or (b) volcanic activity has persisted for a much longer period of time at the southeast end of the range than at the northwest end. If the first hypothesis is correct, the Hawaiian Swell probably represents a progressive phenomenon which may be expected to extend further to the southeast with time.

Hawaiian volcanics--The observable lavas of the Hawaiian Islands according to STEARNS [1946] are predominantly olivine basalts with some late flows of andesite and trachyte. For the most part all of the lavas appear to have a highly vesicular texture resulting in a variable density That this vesicular structure continues with depth is suggested by the fact that basic water-table level on the islands regardless of elevation conforms on the whole to sea level rather than to topography [STEARNS and VAKSVIK, 1935]. This phenomenon would be expected with vesicular

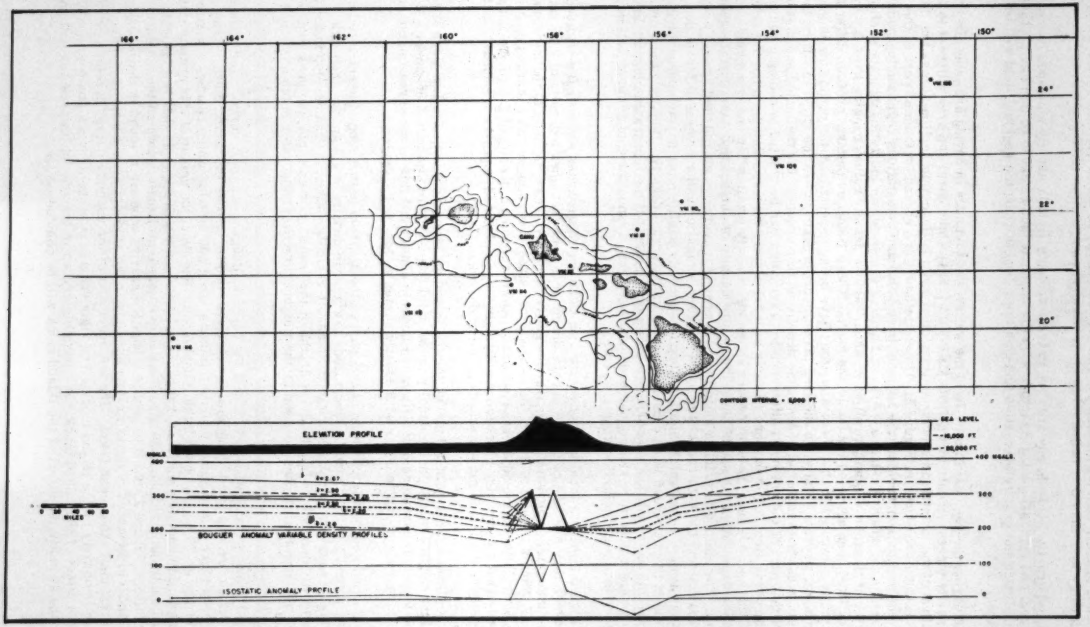


Fig. 2--Location of gravity traverse across Hawaiian Swell and Bouguer- and isostatic-anomaly profiles

lavas because of their high permeability. The overall density of the lavas is therefore likely to be considerably less than that indicated by their mineral composition (2.86 gm/cc).

Regional gravity field--In any area the gravity-anomaly field is usually a composite one reflecting local and regional geologic factors with the regional factors apt to be dominant. Therefore, in analyzing the gravity anomalies found on the island of Oahu the regional field will be considered first.

For studying the regional gravity field the writer was fortunate in having available the trans-Pacific gravity measurements of VENING MEINESZ [1934] which cover the area adjacent to Oahu. The locations of the submarine gravity stations used and a bathymetric section across the Hawaiian Swell at Oahu are shown in Figure 2. Three stations were chosen on Oahu as part of this analysis; one station representing the regional base value and two stations representing points of local superimposed gravity maxima. Also in Figure 2 are shown an isostatic-anomaly profile and a series of Bouguer-anomaly profiles in which various density values ranging from 2.0 to 2.67 gm/cc have been assumed for the island mass. These Bouguer-anomaly profiles differ from those normally computed in that the sea stations have been corrected for the deficiency in mass of the sea water present relative to the land mass. This procedure has the effect of filling the ocean-basin areas with material of the same density as that assumed for the island and thus bring into relief that part of the observed difference in gravity that can be related to geologic causes beneath the ocean floor. The purpose in using several density values is to determine the actual density of the island mass. This procedure known as "density profiles" is one commonly used in subsurface exploration for establishing the in situ density of surface and near-surface geologic formations. The method in brief is as follows. A gravity traverse is established across a topographic feature and the data reduced to yield Bouguer anomalies using several different density values. That density value which yields a Bouguer-anomaly profile most nearly approaching a straight line is the one which most closely approaches the actual density. Density values greater or less than this value will show a correlation with topography. If the topographic feature is one related to geologic structure rather than erosional agencies, a smooth regional curve will be obtained rather than a straight-line anomaly profile.

If in Figure 2 the two local gravity maxima on Oahu are disregarded and only the regional curve on which they are superimposed is considered, it is seen that when a density of 2.67 gm/cc is used the island mass appears as a marked negative-anomaly area compared to the surrounding ocean area. When a density of 2.0 gm/cc is used, the island mass appears as a marked positive-anomaly area relative to the adjacent ocean area. However, when a density of 2.3 gm/cc is used, a smooth regional curve which approaches a straight line is obtained, and this presumably is the in situ density of the island mass as a whole above the ocean floor.

At first glance a density of 2.3 gm/cc for the island mass appears to be too low since the predominant lava, olivine basalt, has a density in the solid state of approximately 2.86 gm/cc. However, if the vesicular structure of the Hawaiian lavas is considered this is not unreasonable since such lavas have been known to occur with density values as low as 1.0 gm/cc.

The principal geologic implication of this part of the analysis is that since the entire island mass rising some 15,000 ft from the ocean floor has a mean density of 2.3 gm/cc, then either there has been considerable subsidence of the mass or vesicular structure can develop under the high confining pressures found in the great depths of the ocean. For example, the pressure on the ocean floor off the Hawaiian Swell caused by the weight of the overlying water column is about 6,700 lb/in^2.

Regional anomaly analysis--In Figure 3 the residual Bouguer-anomaly curve based upon a density of 2.3 gm/cc is plotted along with the elevation profile across the island block. From these it is seen there is a regional gravity minimum about 500 mi wide which reaches a maximum amplitude of about -75 mgals beneath the island block. However, the center of this gravity minimum is displaced about 100 km from that of the island block which suggests that two geologic features are contributing to the anomaly. This is even more strikingly shown on the isostatic-anomaly profile in Figure 2. On this profile a positive gravity anomaly is found in the island-block area and a pronounced negative gravity anomaly in the adjacent area where there is a marked depression in the ocean floor. The left-hand part of the anomaly curve therefore probably is controlled primarily by the island block. The right-hand part probably has a composite control reflecting the effect of the island block and a possible graben in the area of lowered sea bottom. In studying the anomaly the effect of the island block will be considered first.

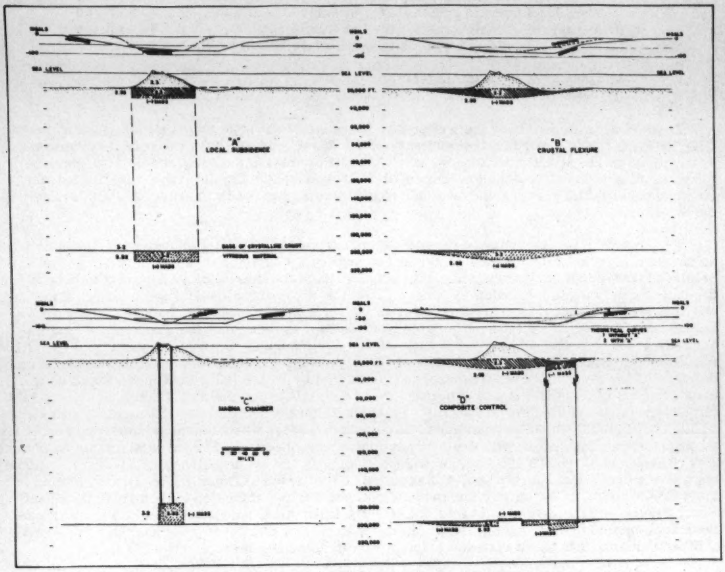


Fig. 3--Comparison of observed and theoretical gravity effects for various subsurface mass distributions beneath the Island of Oahu

There are four mechanisms whereby a deficiency in mass can be associated with a volcanic island. These are: (1) local subsidence of the island block; (2) regional subsidence (crustal flexure); (3) regional thinning of the crystalline crust due to the withdrawal of magmatic material; and (4) the presence of a magma chamber. Under (1) and (2), surface material of mean 2.3 gm/cc density is brought into juxtaposition at depth with normal oceanic crustal material of an estimated 2.95 gm/cc density. Under (3) and (4), it is assumed that there is a decrease in density at depth in the zone of plastic flow as postulated by DALY [1933]. Therefore, under conditions (3) and (4) there would be a change from crystalline basic rock material of approximately 3.2 density to vitreous material of estimated 2.82 gm/cc density at the boundary of the magma chamber and the boundary of the asthenosphere at the base of crystalline crust if such a zone actually exists.

All four of the above mechanisms presumably could be active. However, subsidence of the gabbroic crust of 3.2 gm/cc density into an underlying asthenosphere of 2.82 gm/cc density would give rise to an excess mass at depth whose gravitational effect would counteract that of the deficiencies in mass associated with the downward displacement of low-density surface material and the hypothetical magma chamber.

With so many variables it is obvious that no unique solution can be obtained as to the exact mass distribution causing the observed regional gravity anomaly. However, by assuming reasonable limiting geologic conditions the maximum development of the individual features contributing to the anomaly can be ascertained. These results can then be used to test various theories as to the cause of the anomalies.

The limiting geologic conditions assumed in the following analyses are:

(a) Density of surface volcanic flow material and sediments . 2.3 gm/cc
(b) Density of oceanic crustal layer at surface ..... 2.95 gm/cc
(c) Density of oceanic crustal layer at base ..... 3.2 gm/cc
(d) A uniform increase in density from top to bottom of the crustal layer
(e) Density of vitreous material or magma ..... 2.82 gm/cc
(f) Depth of asthenosphere under Oahu ..... 65 km

In deciding upon the above the writer was influenced to a large extent by the conclusions of GUTENBERG [1945] regarding the structure of the Earth's outer shell, the recent seismic investigations in the Atlantic area by W. M. Ewing of Columbia University and by J. B. Hersey (described by personal communications in 1949) of Woods Hole Oceanographic Institution, the conclusions of DALY [1933] regarding subcrustal conditions, and the studies by JONES [1938] of earthquakes in Hawaii.

Assumption (1) The anomaly results entirely from local crustal subsidence. Under this assumption, surface volcanic flow material and sediments having a mean density 2.3 gm/cc are displaced downward into juxtaposition with oceanic crustal material of 2.95 gm/cc density. Since the deficiency in mass lies below the ocean floor, the width of the base of the island of Oahu which is about 200 km (115 mi) can be used as a first approximation for the width of the area of subsidence. Using the above density values and width it is found that the observed -75 mgals anomaly could be produced by a subsidence of the upper surface of crustal layer of 3.0 km (9,100 ft). However, such subsidence would result in a downward displacement of the lower surface of the crystalline crust into the asthenosphere postulated by DALY [1933] and there would be a counter effect of 14 mgals due to protuberance of crystalline material of 3.2 gm/cc density into vitreous material of 2.82 gm/cc density. In order to have a net effect of -75 mgals a subsidence of 3.5 km (10,600 ft) must be postulated. If no asthenosphere is assumed and a normal transition to denser crystalline rocks with depth is postulated, the observed 75-mgal effect could be obtained by a subsidence of from 8,000 to 8,500 ft depending upon the crustal structure assumed. Although the above assumptions satisfy the local anomaly on the island of Oahu, the mass distribution for local subsidence will not satisfy the anomaly observed at a distance of 150 km from the island. From Figure 3A it is seen that at this distance the theoretical anomaly would be zero whereas the actual anomaly is -35 mgals. Note: In the interests of clarity only one computed anomaly profile is shown, that based upon the existence of an asthenosphere.

Assumption (2) The anomaly results entirely from regional crustal flexure. Under this assumption, a large lens of low-density surface material is displaced downward into juxtaposition with denser material. The local displacement under the center of the island block is essentially the same as that determined for local subsidence. In determining the lateral extent of the lens of surface material, trial and error calculations on the basis of widths of 400, 500, and 600 km were made. The final figure adopted had a central area 70 km wide corresponding to the width of the island platform (roughly 200-fathom contour) over which the displacement was 2.7-3.5 km (depending on the crustal structure assumed) and an overall width of 500 km (310 mi). This mass distribution gives a theoretical anomaly curve which approximates very closely the observed curve for the western side of the profile, but only accounts for about half of the observed anomaly on the eastern half (see Fig. 3B).

Assumption (3) The anomaly results entirely from a magma chamber within the gabbroic crust filled with material of 2.82 gm/cc density in contrast to crystalline wall rock material of 3.20 gm/cc density. As a first approximation as to the depth of this hypothetical magma chamber the focal depth of earthquakes originating beneath sites of active volcanism on the island of Hawaii can be used. JONES [1938] found that whereas the shallow-focus earthquakes on the island of Hawaii had a random distribution, those whose focus lay at depths greater than 40 km were concentrated near the vent of Mauna Loa. No focal depths greater than 65 km were observed and it was also observed that the boundaries of earthquakes of deep focus approximated an eight-pointed star centered on Mauna Loa. The mean radius of this area of deep-focus earthquakes is about 35 km. Since no earthquakes originated below 65 km this is taken as the lower limiting boundary of the top of the magma chamber. Using the above density contrast, depth, and a magma-chamber radius equal to that of the boundary described by the deep-focus earthquakes (35 km), it is found that the chamber would have to have a depth of 7.3 km to satisfy the local anomaly observed on the island. However, as seen from Figure 3C, the regional theoretical curve for such a mass distribution would not give a fit with the observed values beyond the boundaries of the island.

Assumption (4) The anomaly results entirely from thinning of the crystalline crustal layer overlying an asthenosphere due to the removal of magmatic material furnishing the lavas composing the island block. This theory implies an infinitely strong crust and visualizes the void

created by the transfer to the surface of subcrustal material being filled by lower-density materials at the expense of the overlying crystalline crust, the change in state being induced by the lower resulting pressures. Assuming the depth of the asthenosphere to be 65 km and the density contrast to be between vitreous or fluid material of 2.82 gm/cc density and crystalline material of 3.2 gm/cc density, it is found that a thinning of approximately 7 km (21,000 ft) would be required to produce a 75-mgal effect. With this central thickness and a lens shape extending out to 250 km the observed anomaly could be accounted for. However, the mass of material presumably removed to the surface would be about five times that required to form the island block. The maximum development of such a feature having the same mass as the island block would be 2 km assuming a lens shape extending out to 250 km.

That there has been subsidence on Oahu is indicated by bore-hole data, and according to STEARNS (1946) subsidence as great as 1,200 ft is indicated. Subsidence is also suggested by the fact that there is a transition from atolls at the northwest end of the Hawaiian Swell to volcanic islands at the southeast end.

In view of the lack of fit obtained between the theoretical and observed gravity-anomaly curves on the assumption of local subsidence, it appears probable that all subsidence resulted from downward flexure of the crust. Since the crust presumably could support some initial load before being deformed elastically it is possible that some initial thinning of the gabbroic layer may have taken place as a result of the transfer of subcrustal material to the surface. More likely, subsidence went on at the same rate that the magma was withdrawn from depth to be deposited at the surface, and if there has been any thinning of the crust, it has resulted primarily from the displacement of the original crustal boundary into a zone of higher temperatures which might induce a change in state. The mass of material involved in such a mechanism, however, should not exceed that of the extruded lavas. That there is some sort of local magma chamber immediately beneath the point of eruption seems quite likely from the earthquake focal pattern observed around Mauna Loa on the island of Hawaii.

With the above studies and evidence as a background, the writer reconstructed a crustal section which appears to satisfy the observed anomaly pattern to the west of Oahu. The features of this section are: (a) surface subsidence of 3.5 km (10,600 ft) over a central area 70 km wide extending out to zero displacement at a distance of 250 km from the center; (b) crustal thinning amounting to 2 km (6,000 ft) over a central area 70 km wide diminishing at a distance of 250 km from the center to normal thickness; and (c) a magma chamber extending over an area 70 km wide and rising 2 km above the crustal boundary after flexure and crustal thinning. It is obvious, of course, that a simple crustal flexure of about 8,000 ft could account for the anomaly equally well. However, the more complex condition was assumed since it would indicate the maximum amount of crustal deformation.

To satisfy the observed anomaly pattern to the east of Oahu as well, it is necessary to postulate an additional mass deficiency in that area. In view of the depressed sea floor in the area, a graben appears to be the most logical feature to assume. In order to obtain a fit with the observed anomaly curve, the effect of this feature must be approximately 35 mgals. To obtain such an anomaly it is necessary to postulate a down-dropped block about 6,000 ft thick if the mass deficiency is assigned to the upper crust, or about 7,500 ft if it is assumed that the entire crustal column has undergone displacement and there is an asthenosphere. The width of the block involved is taken as being the same as that of the depressed area in the ocean floor which is approximately 100 km. Both mass distributions give similar anomaly patterns and there is little to choose between them. However, since it is found that most grabens in continental areas have very strong gravity anomalies associated with them which can only be explained by the assumption that they penetrate to great depths, the writer has chosen for purposes of illustration a possible trans-crustal fault structure with 7,500 ft displacement. The net theoretical anomaly curve for the various effects discussed and the final hypothetical crustal section evolved is shown in Figure 3D.

Local gravity field--In Figure 4 are shown Bouguer-isoanomaly contours superimposed upon a schematic geologic map of the island of Oahu and two geologic and gravity profiles across the island. From these it is seen that two gravity maxima occur with peak values of about 310 mgals each which is 110 mgals greater than the regional value. It is significant that these two gravity maxima center over the sites of the ancient volcanic caldera of Koolau and Waianae which are regarded as being the original and primary sources of material comprising the island. In the case of each of these ancient volcanoes the seaward slope has been cut back by marine erosion practically to the original central vent area, and it is only on the landward side where the flows of the two overlapped to produce the present high interior plateau area around Schofield that the original topographic profile is preserved.

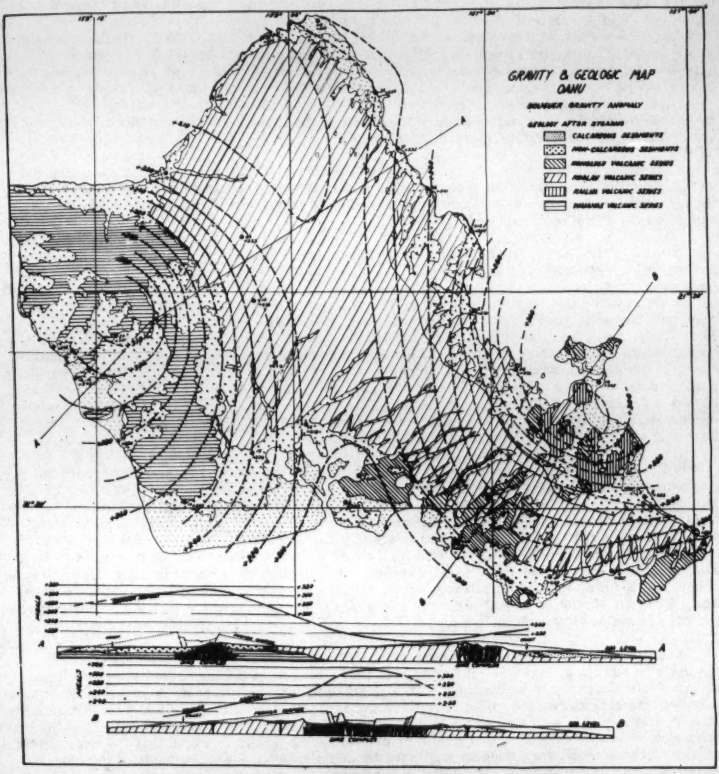


Fig. 4--Geologic and gravimetric map of Island of Oahu and comparative geologic and gravimetric profiles

The positive anomalies at these sites of early eruptions appear to be the result of a contrast in density between the solid throat material in the volcanic vents and the surrounding vesicular basalts. It is significant that the rather symmetrical anomaly pattern associated with the ancient volcanoes of Waianae and Koolau is not perceptibly distorted at the sites of later volcanic activity such as Diamond Head, Koko Crater, the Punch Bowl, or Salt Lake. The explanation of this phenomenon appears to lie in the difference in lithology of the early- and late-stage lavas and in the size of the early and later volcanic pipes. As pointed out earlier, according to STEARNS [1939] the first lavas were dominantly olivine basalts with augite and peridotite inclusions; the later volcanics were more feldspathic and tended to be andesites and trachytes, and the last volcanics were apt to be nephelitic and consist principally of vitric tuffs. If the density changes indicated by these changes in petrology are evaluated along with the density changes ascribed to the difference in rock texture of volcanic throat material and flow material resulting from the liberation of gas in the latter, the gravity-anomaly pattern is in large measure explained (see Table 3).

Table 3--Comparative density data for Hawaiian rock types[a]

Rock type	Lava (solid)	Vitric (glass)	Vesicular (bulk of flows) estimates	Hypabyssal (throat of vent)
	gm/cc	gm/cc	gm/cc	gm/cc
Trachyte	2.53	2.45	1.0 plus	2.72
Andesite	2.60	2.47	1.0 plus	2.82
Basalt[b]	2.86	2.77	1.6 plus	2.95

[a]Based on mean values from WASHINGTON [1917].
[b]Basalt contains peridotite inclusions.

If the additional factor of the relative size of the basaltic volcanic vents and the later-stage more acidic lava vents is taken into consideration the absence of pronounced anomalies at the later volcanic vents appears to be satisfactorily accounted for. The diameter of the ancient Koolau crater was about four miles. That of the Waianae crater was about three miles. An examination of the size of 13 late-stage volcanic craters showed they varied from a fourth mile in diameter to one mile in diameter with an average value of approximately a half mile. Therefore, on the average the volume of material in the throat of a late-stage volcano assuming the same depth of pipe would only be approximately 1/50 that of one of the two early volcanoes.

Analysis of local anomaly pattern--As in the case of the regional anomaly it is possible to use the residual local anomaly to compute a probable depth of subsidence of the island on the basis of the depth to which the contrast in density between throat material and flow material exists. As a first approximation it can be assumed that the mean density of the island mass as determined from the density profiles in the regional study (2.3 gm/cc) is about that of the local flow material. The throat material filling the vent from the surface to the lava source consists presumably of solid basalt of 2.86 gm/cc density near the surface and its hypabyssal equivalent, gabbro of 2.95 gm/cc density, or denser subcrustal material at depth and as a first approximation a mean density of 2.9 gm/cc can be assumed. Using the Koolau crater anomaly (+110 mgals), a diameter of four miles, the above density values, and assuming the vent approximates a vertical cylinder, the depth can be computed from the relation

$$F = G(2\pi)\, d\, [\sqrt{c^2 + h^2} - \sqrt{c^2 + (h + t)^2} + t] \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

in which G = gravitational constant, d = density differential, c = radius of cylinder, h = depth to top of cylinder (zero in this case), and t = depth of cylinder.

(Note: In analyzing the regional anomaly a graticule for determining the gravitational effect of two-dimensional bodies was employed to determine the theoretical effects of the postulated mass distributions.)

Substitution in (1) with the above quantities yields a depth of 7.9 km (24,000 ft) to the base of the volcanic flow material which corresponds to a depth of 9,000 ft below the present ocean floor. This depth is of the same order of magnitude as the subsidence determined from the analysis of the regional gravity anomaly pattern (8,000 to 10,800 ft) and essentially corroborates it.

The isostatic anomaly--Since the isostatic-anomaly profile shows that the island mass is regionally 50 mgals under-compensated in contrast to the adjacent oceanic areas which are essentially in perfect isostatic equilibrium, it is possible to determine the depth of additional subsidence that would be required to bring the island column into isostatic equilibrium. This is found to be about 7,000 ft which would mean a total subsidence of about 15,000 to 18,000 ft. GUNN [1943] on the assumption of isobaric equilibrium rather than isostatic equilibrium has determined a maximum subsidence of about 14,000 ft for the present island mass. Any additional subsidence beyond this figure would presumably have to result from additional mass added by the growth of coral.

Comparison with other areas--Although there are no known seismic depth determinations on the island of Oahu or deep bore holes, there are data that appear to support the general findings of the present investigation. DOBRIN, PERKINS, and SNAVELY [1949] found from seismic depth determinations on Bikini atoll that the upper calcareous cover having a velocity of 11,000 ft/sec terminated in higher speed material of 17,000 ft/sec (presumably volcanics) at a depth of 7,000 ft below sea level in the central lagoon region and 13,000 ft below sea level in the peripheral areas. This would indicate that subsidence of at least 7,000 ft had taken place and possibly 13,000 ft. Unfortunately there were no accompanying gravity measurements, and a rigorous comparison with Oahu cannot be made. Qualitatively though, the results appear to be in good agreement.

. That the situation found on Oahu may well be common to most oceanic islands that have originated through volcanism is suggested by gravity measurements on other volcanic islands. Gravity observations on Johnston and Kwajalein atolls by WOOLLARD [1950], and Bermuda, the Azores, Canary Islands, and Madeira by VENING MEINESZ [1934], and on Hawaii by the U. S. COAST AND GEODETIC SURVEY [1930] have all indicated a lack of isostatic equilibrium. The positive isostatic anomalies associated with such islands appears to be not due to high-density volcanic rock material as many investigators had previously supposed, but rather to the replacement of the sea-water column with a rock column without complete isostatic compensation. Partial compensation apparently is achieved, and possible mechanisms are: (a) horizontal migration of subcrustal material; (b) local subsidence, accompanying regional downwarping of the upper crustal layer; (c) thinning of the overlying crystalline crust; and (d) formation of a magma chamber. None of these mechanisms fit the classical ideas embodied in the Pratt and Airy theories for achieving isostasy, and it is questionable whether complete isostatic equilibrium could be obtained for this type of geologic structure using the standard methods of isostatic reduction.

Acknowledgments--The writer would like to acknowledge the assistance extended by the Honolulu Office of the U. S. Coast and Geodetic Survey in locating pendulum bases, transportation, and assistance in carrying out the field work. The measurements were made as part of the global gravity program being conducted by the writer under the auspices of the Office of Naval Research through the Woods Hole Oceanographic Institution.

References

BETZ, F., and H. H. HESS, The floor of the North Pacific Ocean, Geogr. Rev., v. 32, p. 111, 1942.
DALY, R. A., Igneous rocks and the depths of the Earth, McGraw-Hill, 1933.
DALY, R. A., The floor of the ocean, Univ. of North Carolina Press, Chapel Hill, 1942.
DOBRIN, M. B., B. PERKINS, JR., and B. J. SNAVELY, Subsurface constitution of Bikini Atoll as indicated by a seismic refraction survey, Bull. Geol. Soc. Amer., v. 60, pp. 807-828, 1949.
DUERKSEN, J. A., Gravity anomalies and meridian deflections in Hawaii, Trans. Amer. Geophys. Union, pp. 34-39, 1943.
GORANSON, R. W., The density of the island of Hawaii and density distribution in the Earth's crust, Amer. J. Sci., 5th Ser., v. 16, pp. 90-120, 1928.
GUNN, ROSS, A quantitative study of isobaric equilibrium and gravity anomalies in the Hawaiian Islands, J. Franklin Inst., v. 236, pp. 373-390, 1943.
GUTENBERG, B., Variations in physical properties within the Earth's crustal layers, Amer. J. Sci., v. 243A, 1945.
JONES, A. E., Empirical studies of some of the seismic phenomena of Hawaii, Bull. Seis. Soc. Amer., v. 28, pp. 313-387, 1938.
STEARNS, H. T., Geologic map and guide to Island of Oahu, Bull. 2, Div. Hydrography, Hawaii, 75 pp., 1939.
STEARNS, H. T., Geology of the Hawaiian Islands, Bull. 8, Div. Hydrography, Hawaii, 106 pp., 1946.
STEARNS, H. T., and K. N. VAKSVIK, Geology and groundwater resources of the Island of Oahu, Hawaii, Bull. 1, Div. Hydrography, Hawaii, 478 pp., 1935.
U. S. COAST AND GEODETIC SURVEY, Principal facts for gravity stations in Hawaiian Islands, 1930.
VENING MEINESZ, F. A., Gravity over the Hawaiian Archipelago and over the Madeira area, Proc. Nederl. Acad. Wetensch, v. 44, 1941.
VENING MEINESZ, F. A., J. H. F. UMPGROVE, and Ph. H. KUNEN, Gravity expeditions at sea, v. 11, pp. 1123-1132, Netherlands Geodetic Comm., Delft, 1934.
WASHINGTON, H. S., Chemical analysis of igneous rocks, U. S. Geol. Surv. Prof. Paper 99, 1201 pp., 1917.
WOOLLARD, G. P., The gravity meter as a geodetic instrument, Geophys., v. 15, pp. 1-29, 1950.

Department of Geology,
University of Wisconsin,
Madison, Wisconsin, and
Woods Hole Oceanographic Institution,
Woods Hole, Massachusetts

(Manuscript received November 17, 1950; presented at the Thirty-First Annual Meeting, Washington, D. C., May 1, 1950; open for formal discussion until November 1, 1951.)

Transactions, American Geophysical Union Volume 32, Number 3 June 1951

TIDE-PRODUCING FORCES AND ARTESIAN PRESSURES

William O. George and Frederick E. Romberg

Abstract--Data are presented to show the relationship of changes in gravity and fluctuations in artesian pressure, and atmospheric pressure, as shown by simultaneous measurements. Computed tide-producing forces are also shown. The curves are generally conformable.

The effect of changes in atmospheric pressure upon artesian pressure has been shown [for example, see PIPER, 1932]. ROBINSON [1939] pointed out that artesian pressure, after correction for atmospheric pressure changes, could be shown to conform to Earth tides. LAMBERT [1940] has also discussed Earth tides in relation to water levels in wells. PARKER and STRINGFIELD [1950] have recently published data from Florida with a discussion of the various factors affecting water levels in wells. The following data represent simultaneous observations, made during a 48-hour period, of gravity-meter observations, atmospheric pressure, and artesian pressure at a single locality. The computed tide-producing force is also shown.

Figure 1 shows the results of observations made from 18h 00m on November 30, 1949, to 19h 30m on December 2, 1949, at the M. R. Gonzales artesian water well, about one mile south of Fort Stockton in Pecos County, Texas. The well is about 700 km and more than 1300 km, respectively, from the Gulf Coast and the Pacific Coast at the nearest points. According to NISHIMURA [1950], the effect of ocean tides should be negligible.

Graph I in Figure 1 shows gravity-meter observations at 15-minute intervals throughout the 48-hour period. The gravity meter was placed on the ground about 50 ft from the water well. Graph II shows the computed or theoretical tidal force on the Earth's surface caused by the Sun

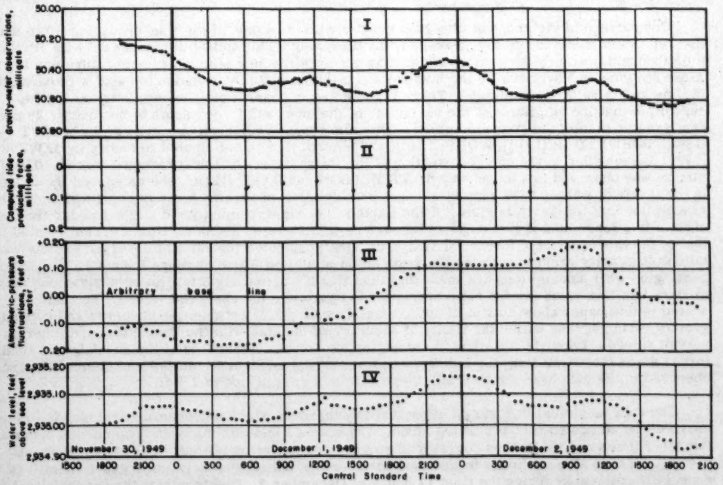


Fig. 1--Gravity-meter, atmospheric-pressure, and artesian-pressure measurements, and computed tide-producing forces at Gonzales artesian well near Fort Stockton, Texas

and Moon. Graph III shows the fluctuations in atmospheric pressure obtained by means of a recording barograph stationed about one mile north of the well. Graph IV shows the fluctuations in artesian pressure as taken from a chart from a continuous water-stage recorder, the setting of which was checked by the wetted-tape method.

The water well is 240 ft deep and the depth to water is approximately 43 ft below the top of the casing, which is 2.973 ft above mean sea level. The principal water-bearing formation is limestone. The underlying sandstone, as shown in Table 1, probably contributes some water to the well.

Table 1--Driller's log of Gonzales artesian well

Material	Thickness	Depth
	ft	ft
Adobe	5	5
Lime, soft chalk	7	12
Caliche	6	18
Hard lime	27	45
Open cavity	4	49
Gray or light-blue lime	39	88
Gray water sand	22	110
Red clay, yellow clay, blue shale, and hard lime	130	240

The rocks are of Lower Cretaceous age, and, according to data published by ADKINS [1927], the well is near the axis of a northward-plunging syncline. The Kismichi formation is exposed near the well and presumably makes up the upper part of the section penetrated.

Partial relief of artesian pressure is provided by Comanche Springs, about one mile north of the well, which have a combined average flow of about 19,000 gal/min from several openings. The water issues from crevices in limestone, probably enlarged by solution along fractures or possible minor faults. Pumping from wells for the city of Fort Stockton, believed to be from the same source, is automatically controlled. Withdrawals for the city may have ranged to 1000 gal/min during the period of observation, but the withdrawals had no measurable effect on the water level in the observed well.

Comparison of the graph of observed gravity with the graph of the tide-producing force shows that the two conform fairly well, except at the beginning. This initial difference may be attributed to instrumental error; the gravity meter may not have reached a state of temperature equilibrium. After 23h 00m on November 30 the maxima and minima in both curves correspond with each other in time and in relative amplitude. There is, however, a general discrepancy between the two curves, in that the amplitude of the variations of the observed force seems to be roughly 25 per cent greater than in the computed curve. This discrepancy has been observed by LAMBERT [1940], SCHWEYDAR [1914], WOLF [1940], and others. It was anticipated in theory by LOVE [1909] as being due to the actual distortion of the Earth under the tide-producing forces. The distortion was observed in another way by MICHELSON and GALE [1919], who measured the changes in the levels of water at the ends of a long pipe. The tide-producing force is computed under the assumption that the Earth is rigid. If the Earth is not rigid, it must yield slightly under the influence of this force, and if it does yield its surface will move up and down with a period related to that of the tide-producing forces. TAKEUCHI [1950] computes the ratio of observed gravity variations to gravity variations under the assumption of a rigid Earth to range from 1.15 to 1.19, depending on what assumptions are made as to the Earth's actual rigidity. He quotes various authors to show that this value for the ratio corresponds roughly to the observed values. The data presented in this paper show a ratio of approximately 1.25 ± 0.05 between the observed and computed gravity, which agrees within the limits of accuracy of the data with the theoretical and other observed values. Takeuchi's method of computing the actual deformation of the Earth by the tidal forces gives the result that, for a deforming force of 0.2 milligal (about the maximum difference observed in the data here considered), there will be a crustal tide of 1.3 ft.

The data as plotted in Figure 1 show that the curve of artesian pressure corresponds to the curve of the computed tide-producing force. The maxima and minima of the two curves occur at the same times and the curves correspond roughly in relative amplitude. The curve of atmospheric pressure also conforms to the tidal-force curve, but less closely; divergence from it is especially noticeable during the first 12 hours of December 2. In this period the general level of the atmospheric pressure is about 0.2 inch of mercury higher (0.2 ft of water), whereas the average water level stays the same as it was. This suggests that the fluctuations in atmospheric

pressure may be less important than the Earth tide in causing the diurnal fluctuations of the water level.

Acknowledgments--Gravity-meter readings were made by Doyle B. Knowles, Thomas M. Culbertson, and James W. Hood. The writers are grateful to M. R. Gonzales for use of his water well, and to the firm of LaCoste and Romberg for the use of a gravity meter.

References

ADKINS, W. S., The geology and mineral resources of the Fort Stockton quadrangle, Texas Univ. Bull. 2738, 1927.

LAMBERT, W. D., Report on Earth tides, U. S. Coast and Geodetic Survey, Spec. Pub. 223, 1940.

LOVE, A. E. H., The yielding of the Earth to disturbing forces, Proc. R. Soc. London, v. 82, pp. 73-82, 1909.

MICHELSON, A. A., and H. G. GALE, The rigidity of the Earth, Astrophysics J., v. 50, pp. 330-345, 1919.

NISHIMURA, EIICHI, On Earth tides, Trans. Amer. Geophys. Union, v. 29, pp. 357-376, 1950.

PARKER, G. G., and V. T. STRINGFIELD, Effects of earthquakes, trains, tides, winds, and atmospheric-pressure changes on water in the geologic formations of southern Florida, Econ. Geol., v. 45, pp. 441-460, 1950.

PIPER, A. M , Geology and ground-water resources of The Dalles region, Oreg., U. S. Geol. Survey, Water-Supply Paper 659, pp. 109-189, 1932.

ROBINSON, T. W., Earth tides as shown by fluctuations of water levels in wells in New Mexico and Iowa, Trans. Amer. Geophys. Union, pp. 656-666, 1939.

SCHWEYDAR, W., Harmonische Analyses der Lotstörungen durch Sonne und Mond, SitzBer. Preuss. Akad. Wiss., no. 59, 1914.

TAKEUCHI, HITOSHI, On the Earth tide of the compressible Earth of variable density and elasticity, Trans. Amer. Geophys. Union, v. 31, pp. 651-689, 1950.

WOLF, ALFRED, Tidal force observations, Geophysics, v. 4, pp. 317-320, 1940.

Additional bibliography

ELKINS, T. A., Nomograms for computing tidal gravity, Geophysics, v. 8, p. 134, 1943.

WYKOFF, R. D., The Gulf gravimeter, Geophysics, v. 6, pp. 13-33, 1941.

Ground Water Branch (W.O.G.),
U. S. Geological Survey,
Austin, Texas

LaCoste and Romberg (F.E.R.),
Austin, Texas

(Communicated manuscript received January 17, 1951;
open for formal discussion until November 1, 1951.)

ADDITIONAL NOTES ON A SEMI-RIGOROUS METHOD OF ADJUSTING TRIANGULATION NETWORKS

B. Goussinsky

Abstract--This is an addendum to the article "On a Method of Semi-Rigorous Adjustment of Triangulation Networks," which appeared in the Transactions in August 1950 and which described a method of adjusting triangulation networks observed for geophysical or topographical purposes.

The method previously described in "On a Method of Semi-Rigorous Adjustment of Triangulation Networks" in the Transactions of August 1950 is capable of extension. The limitation of the procedure only to the case "when observations are carried out by the method of directions, not by angles, and when there are no enforcing conditions" can be omitted. After consideration I came to the conclusion that the method is applicable in all cases.

Observation method by angles--In this case the horizon equations are satisfied first. These are local conditions, which can be treated independently of each other. Their solution is the first stage of the work. After this first adjustment, the angles at each station, which now invariably total 360°, are resolved into directions, by taking a line of one of them as the reference object for all the others. The remainder of the process is then done as previously described for the "figural," that is, angular-closure and side condition equations, in two subsequent steps. In other words, the total process consists now of three stages: (a) satisfaction of the horizon condition equations, with subsequent resolution of angles into directions; (b) adjustment of angular-closure condition equations; and (c) adjustment of side condition equations. It can easily be seen that here, too, results of any stage of the adjustment are not upset by those following it.

This extension of the procedure to the method of observation by angles is justified by the following considerations:

(1) Preliminary adjustment for closure in horizon--This is analogous to the adjustment of observations by the method of directions, when, before the "figural" adjustment, the directions on each station undergo a preliminary "station" adjustment.

(2) Resolution of angles into directions--As usually admitted, errors are inherent not to angles, but to individual directions, and observations carried out by the method of angles can always be compensated by adjusting the directions into which the angles are resolved.

Enforcing conditions--These belong to the same categories as the free condition equations, that is, those of angular closure and length. The first are adjusted with all the other angular condition equations, by adding to the set, the necessary number of "fixed angle conditions," the object of which is to preserve the given angular difference between any pair of lines fixed in relative bearings. When the adjustment for sides is made, lines fixed in relative length are given the same index ("letter") in the set of indexes for lines under adjustment. The difference of their bearings, after adjustment for side, remains then the same as before, the fixed lines having been corrected by the same amount.

Remarks--The adjustment of a network with lines fixed in bearings and lengths could also be carried out by "ignoring" these lines for any correction. This method, however, though frequently used, should be considered unworthy of least squares, being rather artificial, unsymmetrical, and not similar in form to the free condition equations.

Survey Department,
Tel Aviv, Israel

(Communicated manuscript received January 18, 1951;
open for formal discussion until November 1, 1951.)

Transactions, American Geophysical Union . Volume 32, Number 3 June 1951

PKKP, P'P', AND THE EARTH'S CORE

B. Gutenberg

(Contribution No. 557, Division of the Geological Sciences,
California Institute of Technology, Pasadena, California)

Abstract--Observed times and amplitudes of PKKP and P'P' are discussed. At distances between 100° and 120° PPP with angular distances over 180° precedes P'P' by less than one minute and has occasionally been confused with P'P'. The travel-time curve for longitudinal waves between points on the surface of the core is revised. Observed amplitudes of short-period waves in P' and PKKP are roughly four times greater than the amplitudes calculated on the assumption that the distribution of energy as a function of period is the same for waves through the core as for those through the mantle only (P, PP, and S). PKKP waves with periods of more than three seconds are very rare. PKKP through the inner core is usually not observed, in agreement with theoretical expectation. The fact that PKKP through the outer part of the core is well observed indicates a ratio of probably at least 1.7 for the densities inside and outside the outer core unless the ratio is near 1.0. At the boundary of the inner core (radius about 1300 km) the velocity increases from 10± to 11± km/sec within 100± km and is 11.2± km/sec in most of the inner core. P'' at distances between its beginning near 105° and a distance of about 125° is probably mainly due to waves reflected at the inner core.

"Many theories of the Earth have been propounded at different times: the central substance of the Earth has been supposed to be fiery, fluid, solid, and gaseous in turn, till geologists have turned in despair from the subject, and become inclined to confine their attention to the outermost crust of the Earth, leaving its center as a playground for mathematicians." This statement of OLDHAM [1906, p. 456] is as valid today as it was in 1906. The first attempt to calculate the radius of the Earth's core was made by WIECHERT [1897]. He concluded from theoretical considerations involving the density of the Earth that the radius of the Earth's core (supposed to consist of iron and to be surrounded by a stony mantle) is about three-quarters of the radius of the Earth. OLDHAM [1906] noticed that at great distances the longitudinal waves through the Earth are delayed. He believed that he had found longitudinal as well as transverse waves through the Earth's core and concluded that the radius of the Earth's core is about 2500 km, that in the core "the rate of propagation of the first phase is but slightly reduced, while the second-phase waves are either not transmitted at all, or, more probably, transmitted at about half the rate which prevails in the outer shell." Zoeppritz [WIECHERT and ZOEPPRITZ, 1907, p. 520] immediately pointed out that Oldham had probably mistaken transverse reflected waves (SS) for direct transverse waves. In addition, Oldham combined travel times of P, PP, and P' in one curve. As a consequence, Oldham's results were quantitatively incorrect. The radius of the core which he found is about 1000 km too small.

After WIECHERT [1907, p. 508, footnote] also had noticed that at distances over 100° longitudinal waves arrive relatively late, GUTENBERG [1914] found the depth of the core to be 2900 km (radius 3470 km). (The paper mentioned in Wiechert's footnote, in which he refers to the velocity in the core, is probably the paper "Ueber Erdbebenwellen IV" which never has been printed. See also ZOEPPRITZ [1912, pp. 123-124] with a reproduction of the velocity-depth curve mentioned by Wiechert's footnote, and by WIECHERT [1908, p. 45].) The author's 1914 curve showing the velocity as a function of depth is included in Figure 1. He also calculated travel times of SKS, PKS, PKKP, and other waves through the core.

Much later, WADATI and MASUDA [1934] investigated travel times of longitudinal waves inside the core by subtracting distances and travel times of ScS from the respective values for SKS. The corresponding distances for the two waves are given by the condition that the angle of incidence (and consequently the apparent velocity) of the two phases are the same, or that their travel-time curves have the same slope. Actually, a variety of phases can be used, for example, P'-PcP, SKS-ScS, 1/2(PKKP-PcP), SKP-ScP. (The symbol P' indicates PKP, where P corresponds to the longitudinal wave in the mantle, K in the core. S corresponds to the transverse wave in the mantle, c indicates reflection at the core.) The interpretation by GUTENBERG [1914] resulted in two branches for P' joining in a focal point at a distance of 143± degrees and extending to larger distances. While observations plotted by VISSER [1921] show indications of the two branches,

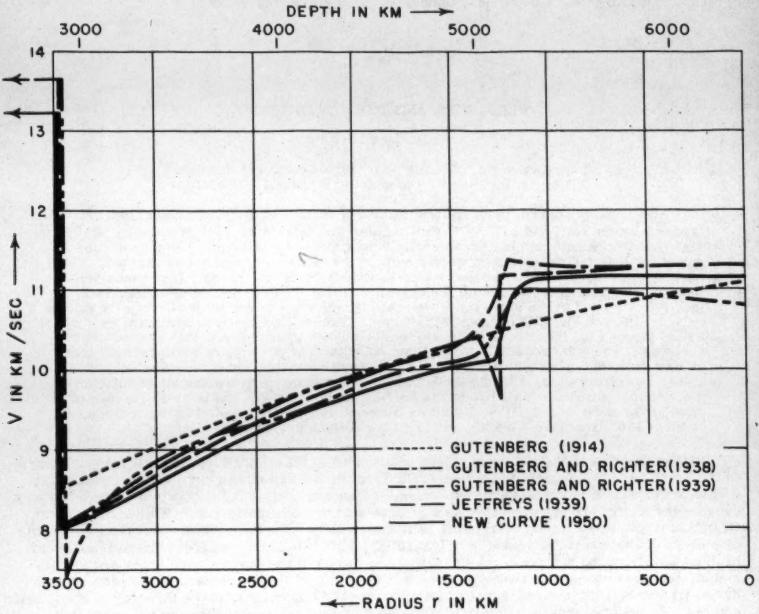


Fig. 1--Calculated velocity V of longitudinal waves in the core

LEHMANN [1930] and MACELWANE [1930] were the first to give detailed observations of the second branch. Both designated the earlier branch by P_1', the later by P_2'.

The focal point was confirmed by amplitude observations [GUTENBERG, 1914, Fig. 3; MACELWANE, 1930]. It is a consequence of "ray optics" and does not correspond to any irregularity inside the core. An expected shadow zone for longitudinal waves at angular distances between about 103° and 143° seemed to be corroborated by the data in 1912. However, RUDOLPH and SZIRTES [1914] and ANGENHEISTER [1921] published observations which they interpreted as indicating that the travel-time curve of P′ branches off from that of PP at a distance of 113° and about 100° respectively [see also VISSER, 1921, p. 27]. This branch of P′, extending from a distance of about 100° to the focal point near 143°, was later indicated by the symbol P″. In 1922, Wiechert (unpublished) presented a paper at the Naturforscherversammlung at Leipzig in which he tried to explain these waves as due to diffraction. LEHMANN [1936] pointed out that P″ is too strong to be caused by diffracted waves, and suggested that it may be explained by a discontinuity separating an outer part of the core with a lower wave velocity from an inner core with a greater velocity.

The suggestion of Miss Lehmann was taken up by GUTENBERG and RICHTER [1938]. They applied the method of WADATI and MASUDA [1934] to P′-PcP and to SKS-ScS, revised the travel-time curve for waves inside the core (see Fig. 2) and calculated the corresponding wave velocities by using the well-known method of Herglotz-Wiechert-Bateman as extended by SLICHTER [1932]. They found that the P″-waves can be accounted for as waves refracted through a relatively thin layer (approximately 300 km thick) at a depth of about 5000 km, in which there is a rapid but probably continuous increase by about 1.2 km/sec of the velocity with depth. The corresponding velocity-depth curve and a revised curve [GUTENBERG and RICHTER, 1939] are included in Fig. 1.

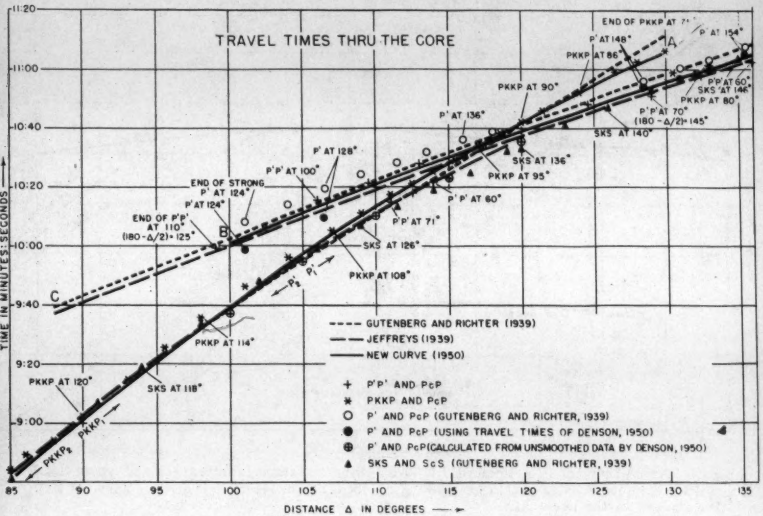


Fig. 2--Travel times for longitudinal waves between points on the surface of the core

JEFFREYS [1939], by extending Airy's theory of diffraction, found that no appreciable amplitudes of a diffracted P' could be expected beyond about 3° from the caustic. He used a great number of observed travel times of the "core phases" in the construction of an improved travel-time curve for the core (see Fig. 2). Jeffreys assumed that true reflection occurs at the inner core, while Gutenberg and Richter had fitted a reversed segment between the two parts of the travel-time curve without supposing reflection. Jeffreys found that on his assumption no agreement is possible, unless the velocity actually decreases with depth in the range of r between about 1400 and 1250 km. He pointed out [JEFFREYS, 1939, p. 600] that he had adopted the hypothesis of reflection for convenience, but "that it may well be true" from various considerations, among which the observed amplitudes of P' played an important role.

The investigations of Gutenberg, Richter, and Jeffreys left little doubt that the absolute values of the travel-time curve through the core (Fig. 2) are well known, but that more accurate values for the slope of this curve, especially near the ends of the segments at A and B, are needed to improve the velocity-depth curve. This slope depends appreciably on the correlation of the travel-time curves, such as P' and PcP, and SKS and ScS, in the construction of the travel-time curve for K.

If the velocity V decreases with depth at a distance r from the center, the travel-time curve remains continuous as long as

$$dV/dr < V/r \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

This is equivalent to the condition that the radius of curvature of the ray at its deepest point exceeds r if V decreases with depth. In the case of Jeffreys' layer with decreasing velocity (decrease by about 3/4 km/sec over a range of about 140 km, r = 1400 km, V = 10 km/sec) this condition is fulfilled, and it should be possible to find this decrease in velocity by the usual integration method if the travel-time curve is well enough known.

The condition for cusps and a reversed segment in case of a gradual but rapid increase in velocity is much more complicated, since it contains the integral which occurs in the Herglotz solution for calculating the deepest point of a ray. Even if the curvature of the Earth is neglected, an integral containing the velocity is involved [SLICHTER, 1932, p. 281].

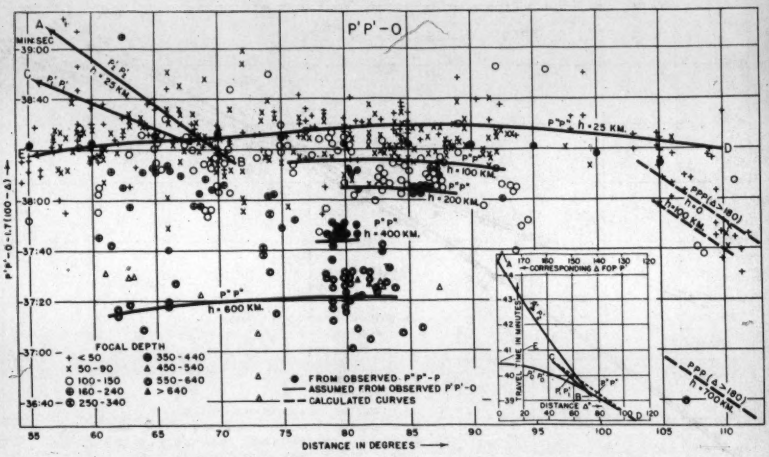


Fig. 3--Travel times of P'P' minus 1.7 (100-Δ) where Δ = distance in degrees and travel times of PPP over the greater arc (Δ over 180°), h = focal depth; insert: travel-time curve of P'P' for shallow earthquakes

Since there is little hope at present of improving the travel-time curves appreciably--this requires among other investigations the study of the practically unknown local effects--a series of investigations of the amplitudes of core waves has been started at the Seismological Laboratory at Pasadena. Studies of waves reflected at the core in shallow shocks [MARTNER, 1950] and deep shocks [ERGIN, in press] indicate that the observed amplitudes of the principal component of these waves (vertical component in PcP and ScP, horizontal component in ScS and PcS) are in fairly good agreement with the theoretical values although most observed amplitudes seem to be slightly too large. The fact that the smaller component in all these waves is too large is apparently not connected with the reflection at the core. This problem is being studied by Ergin.

Amplitudes, periods, and travel times of P' and P'' have been investigated by DENSON [in press], whose results are used throughout this paper. He finds that for waves with periods of not over about two seconds the focal point occurs near 147°, for waves with greater periods at shorter distances down to about 143° The average amplitudes which he observed are indicated in Fig. 10.

The present paper discusses an investigation of travel times, periods, and amplitudes of P'P', which was first identified by GUTENBERG and RICHTER [1934], and of PKKP. (For seismograms showing PKKP, see GUTENBERG and RICHTER [1934a, p. 89]; for P'P', see GUTENBERG and RICHTER [1934b, p. 153]. ZOEPPRITZ [1912, p. 143] considered the possibility of observing P'P'; the phases mentioned by him were probably pP and SKPP'. PKKP was tentatively identified by GUTENBERG [1925, p. 110].) The symbols which are used at present for the various branches of P', P'P', etc., are a result of historic development. P_2' refers to the branch with the largest angles of incidence i_0 at the surface; it begins at an angular distance of over 180° with the ray through the core which grazes it externally and it ends at the main focal point of P' near 143° P_1' begins at this cusp and with further decreasing i_0 extends to greater distances always preceding P_2'. P_1' ends at the point corresponding to the ray tangent to the inner core. (Compare the similar curves for P'P', insert in Fig. 3; the distances at top of the insert correspond to P', the times for P' are about half of those for P'P'.) The following segment, again reversed, (CD in Fig. 3) may correspond to a wave reflected at the inner core and may extend beyond D (corresponding to distances from 125° to 100° in P''). The segment CD has not been identified by observations and has no symbol. The whole remaining segment (DE) corresponds to waves through the inner core. It has no single symbol; at present, P'' is being used for the distances from its beginning (D) to the main focal point (B, which is not on the P''-curve), and the symbol P_1' for the rest.

Table 1--Factor f to reduce measured trace amplitudes m having a period of T seconds to relative ratios a/T for different waves in a given seismogram; a = ground amplitude, Tg = period of galvanometer; the pendulum period is assumed to be one second; a/T = mf

T	Factor f for Wood-Anderson instrument		Factor f for Benioff instrument for various values of Tg (sec)				
	short	long	1/4 sec	1 sec	10 sec	20 sec	90 sec
sec							
1/2	0.7	2.6	0.12	0.4	0.3	0.3	1.2
3/4	0.7	1.7	0.15	0.3	0.16	0.16	0.7
1	0.6	1.3	0.18	0.25	0.13	0.12	0.5
1 1/2	0.7	0.9	0.27	0.3	0.09	0.08	0.33
2	1.0	0.65	0.38	0.4	0.08	0.08	0.30
3	1.6	0.43	0.77	0.9	0.09	0.08	0.25
4	2.2	0.37	1.4	1.8	0.12	0.09	0.22
5	2.6	0.30	2.2		0.17	0.10	0.22

However, this symbol should be used only for the branch BC. In the present paper the symbol P_0 is used for P'' beyond $\Delta = 143°$. Jeffreys uses the symbol PKIKP for the whole branch CD (I refers to longitudinal waves in the inner core, K in the outer core). New symbols should be internationally adopted to permit the use of simple symbols for practical use--avoiding, for example, PKIKKIKP for (PKKP)''--which do not disagree with the theoretical findings (as does at present the use of P_1' for two different paths). For PKKP and P'P' symbols are used in the present paper similar to those for P'; $(PKKP)_1$ and $(PKKP)_2$ correspond to the two phases passing through the outer but not through the inner core, (PKKP)'' (corresponding to $P'' + P_0'$) for that passing through both. $P_0'P_0'$ corresponds to P_0', etc.

On more than 1000 seismograms, practically all of them from shocks of magnitude 6 3/4 or more during the period 1933 to 1949, periods and amplitudes of P, PP, PKKP, and P'P', as well as time intervals of PKKP and P'P' against P (or P' at distances beyond about 110°), were read, mostly from records at Pasadena and its auxiliary stations, but also in some instances from Tucson (seismograms or copies available at Pasadena through the courtesy of the U. S. Coast and Geodetic Survey). Arrival times for PKKP and P'P' at these stations have been read for the past 15 years whenever possible by C. F. Richter and assistants, and frequently also in major and great earthquakes by the author for Pasadena. These times were combined with the origin times of the respective shocks found by GUTENBERG and RICHTER [1949]. Epicentral distances were taken from the original calculations of the epicenters given in the same book. For 1948 and 1949 the corresponding data were taken from similar calculations (results partly published at the end of the Pasadena Bulletin for these years).

During the past 20 years practically all of the Benioff pendulums used in the Pasadena network had a period of about one second, but galvanometers and magnification of the instruments were changed from time to time. For this reason only amplitude ratios could be used. Their calculation from records of electromagnetic instruments depends mainly on the periods of the pendulum and the galvanometer (the damping being kept usually close to aperiodic). Since in the present paper the ground amplitude a was not needed but only its ratio to the corresponding period T (see Eq. 2), this ratio a/T was calculated directly. The term $2\pi a/T$ is the amplitude of the velocity of the ground in sinusoidal waves.

Table 1 gives reduction factors which were based partly on routine magnification curves [GUTENBERG and RICHTER, 1948], partly on values calculated by R. Gilman (who also arranged for the final drafting of figures) at the Seismological Laboratory for various periods T. Since f in Table 1 changes relatively slowly with T, it should usually be possible to find the ratio of a/T for two waves in the same shock within a factor 2 or better or the corresponding difference in the logarithms within ± 0.3.

Ratios of a/T for PKKP/P, PKKP/PP, P'P'/P, and P'P'/PP were calculated from the observations, and for each of these four groups six charts were plotted, one each for the vertical component in shallow, intermediate, and deep shocks and one each for the corresponding horizontal component. Figures 4 and 5 give examples for PKKP/PP, Figure 6 is an example for P'P'/P, and Figure 7 for P'P'/PP. Results for short-period instruments (Tg not over two seconds) and long-period instruments are marked by different symbols; the limit of two seconds was taken considering the different characteristics of f as a function of T for greater and smaller periods (see Table 1).

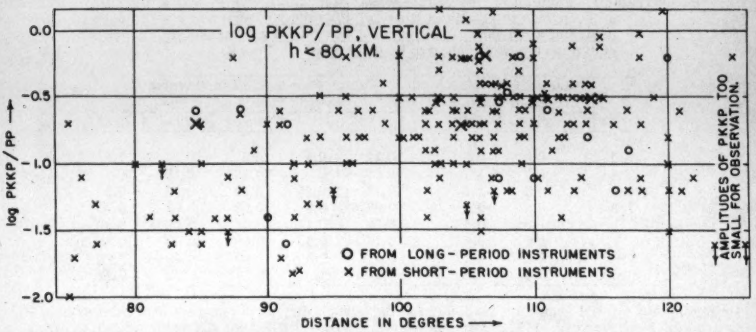


Fig. 4--Log (PKKP/PP) for vertical component of a/T in shocks with focal depth of less than 80 km; a = ground amplitude. T = period

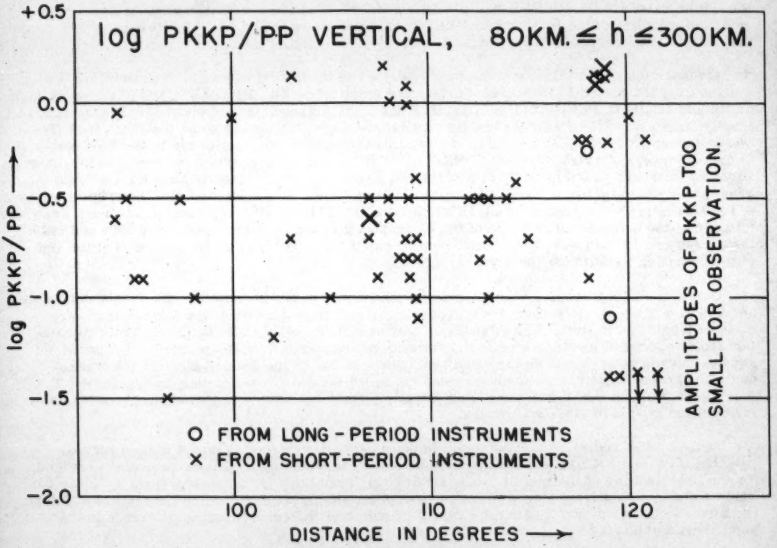


Fig. 5--Log (PKKP/PP) for vertical component of a/T in shocks with focal depth between 80 and 300 km

In general, there was no systematic difference between results derived from records of short-period and long-period instruments.

Plotting of the periods against distance for each of the four waves under consideration indicated that periods of one to two seconds prevailed by far in all four phases in the records of

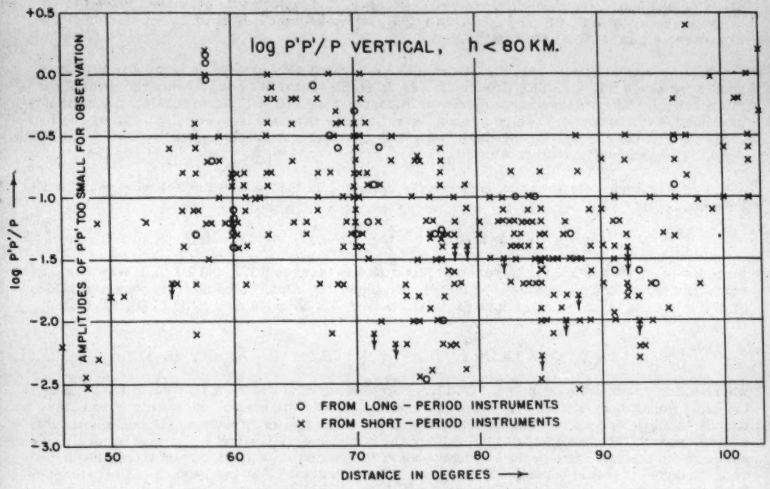


Fig. 6--Log (P'P'/P for vertical component of a/T in shocks with focal depth of less than 80 km; a = ground amplitude, T = period

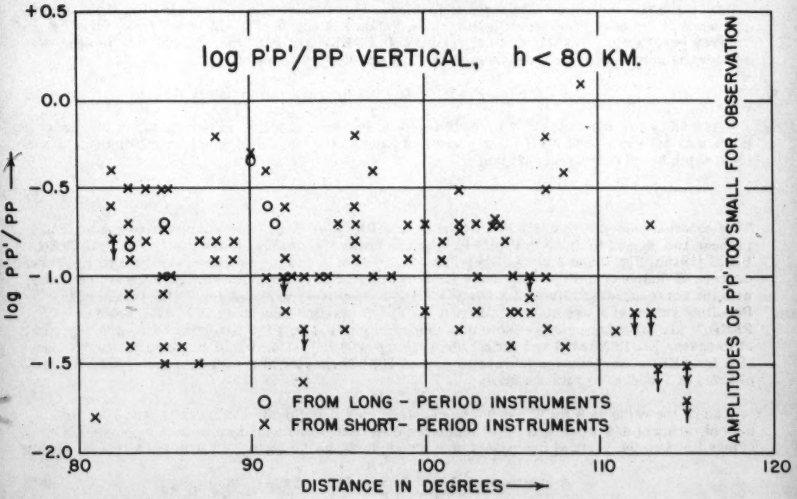


Fig. 7--Log (P'P'/PP) for vertical component of a/T in shocks with focal depth of less than 80 km

short-period instruments, while on records of long-period instruments periods of three to five seconds prevailed in P, PP, and P'P'. In PKKP, waves with periods of three seconds or more are extremely rare on all records.

The horizontal component of PKKP could be measured only rarely. In large shocks it is obscured by waves following SK8 (frequently PS), in small shocks it is at or below the level of the microseisms. The observations--mostly at distances near 110°--indicate horizontal amplitudes of about 1/4 of the vertical, which is near the ratio to be expected theoretically. The theory indicates that, on the average for shocks of a given magnitude, a/T should increase slightly with focal depth. The observations agree with this.

For magnitude determination based on the ratio a/T in body waves the following equation has been used [GUTENBERG, 1945a]

$$M = A + \log a/T + C \qquad C = 0.2\ (M-7) \text{ approximately} \quad \ldots\ldots\ldots\ldots (2)$$

Since for most shocks used in the present paper M was between 6 1/2 and 7 1/2, C was a small correction which usually could be neglected. By use of (2), A can be found from observed values of a/T in shocks of known magnitude M; in addition, A can be calculated [GUTENBERG, 1945a] from

$$A = 6.3 - \log (a/A_t) - 0.5 \log F + 0.2171\ k\ D - 0.5 \log [(\sin i_h / \sin \Delta \cos i_o)\ di_h/d\Delta] \quad \ldots (3)$$

where 6.3 is an empirical constant found from amplitudes of P and S. It is supposed here to be the same for all body waves. This involves assuming that at the source the energy is radiated equally in all directions and that the distribution of the energy as a function of T is the same for all body waves. The term a/A_t is the ratio of the horizontal or vertical component of the ground amplitude to the amplitude of the incident wave at the station; in a given type of wave, longitudinal or transverse, it should depend only on i_o and Poisson's ratio. F is the product of the ratio of refracted or reflected energy--as the case may be--to the incident energy at each discontinuity which the wave has passed. For values of such factors and of a/A_t see GUTENBERG [1944]. The symbol k is the absorption factor; it is probably about 0.12 on the average [GUTENBERG, 1945a, p. 58] if the distance D along the path is measured in megameters (1000 km); in this case 0.2171 k = 0.026; 0.2171 = 0.5 log e. The angle of incidence at the source (focal depth h) = i_h; the angle of incidence at the point of observation = i_o; Δ = distance in degrees; $di/d\Delta$ is to be measured in degrees per degree. For the vertical component of PKKP and P'P' the value of a/A_t is near two, and for the amplitudes of these waves in shallow shocks (3) reduces to

$$A = 6.0 - 0.5 \log F + 0.026\ D - 0.5 \log [(\tan i_o / \sin \Delta)\ di_o/d\Delta] \quad \ldots\ldots\ldots (4)$$

If x and y are the ratios a/T for two waves in the same shock or in two shocks of the same magnitude M, and A_x and A_y the corresponding values of A, considering epicentral distance Δ and focal depth h, it follows from (2) that

$$A_y = A_x + \log (x/y) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

This equation makes it possible to calculate A for PKKP or P'P' from the observed ratios of a/T in these two phases to those in P or PP. For the latter two phases, A has been given by GUTENBERG [1945b, Fig. 2 and 3 respectively] as a function of Δ and h. Average values for a/T, at even degrees of distance, in Figures 4 and 5 (and the other similar unpublished figures) were combined with the corresponding values of A for P and PP respectively to find A for PKKP by use of (5). Resulting values of A are plotted in Figure 8. For Δ smaller than about 100° data based on PKKP/P are probably more reliable than those for PKKP/PP; PP is likely to be abnormally small at Pasadena [GUTENBERG and RICHTER, 1935, pp. 308 ff.]. This would result in too small values of A for PKKP. At distances increasing beyond 103° (beginning of the shadow zone for P) the amplitudes of P decrease rather rapidly.

Since the value of A for P has not been determined thus far for distances beyond 105°, the observed ratios of a/T for P and PP at distances over 100° were used to calculate approximate values for A in the vertical component of P for shallow shocks (using (5)) with the following result:

Δ (degrees)	100	105	110	115	120
A	7.4	7.7	8.1	8.6	(9.2)

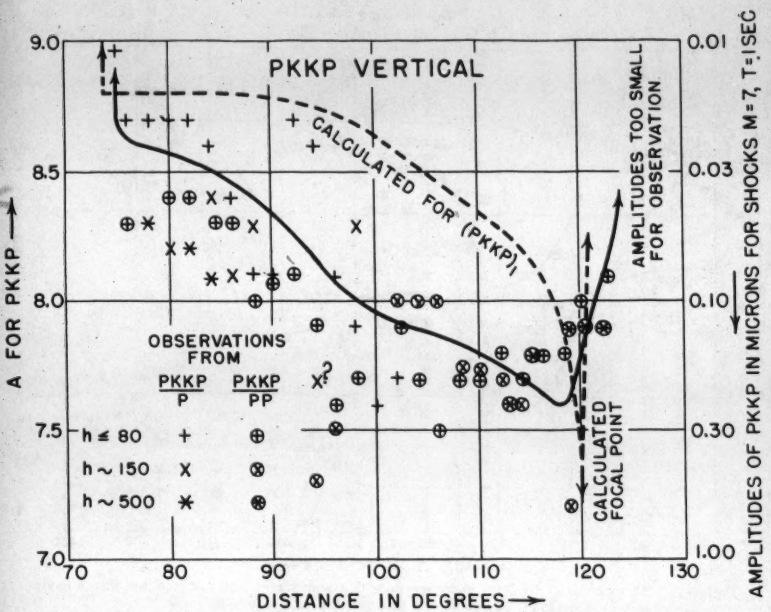


Fig. 8--A = M - log (a/T) for vertical component of PKKP and corresponding ground amplitudes a in microns for waves with a period T of one second in a shock of magnitude M = 7.0

The relatively few data for deep shocks indicate values of the same order of magnitude for A, especially about 8 1/4 for $\Delta = 110°$, h = 200 km; and about 8 1/2 for $\Delta = 118°$, h = 700 km.

Figure 8 does not indicate large differences between the A-values of PKKP for different focal depths. In most cases, A is slightly smaller (relative amplitudes are slightly greater) for greater focal depth, as expected from the theory.

At distances less than 75°, PKKP is usually too small for observation. Figure 8 shows that the relative amplitudes of PKKP (scale on the right) increase rather rapidly with Δ beyond Δ = 75° and reach a maximum near 120° (compare Fig. 5). Beyond $\Delta = 120°$ they decrease rapidly, and are usually again too small for observation beyond 122°. While there are frequently indications of several PKKP phases, it is not easy to identify amplitudes of a given branch. For the study of PKKP, seismograms of relatively large shocks have to be used; the maximum of P then usually occurs an appreciable fraction of a minute after the beginning and similar behavior of PKKP must be expected. Figure 8 refers to the branch with the largest observed amplitudes at each distance, which is probably $(PKKP)_1$ at practically all distances.

The observed ratios of a/T for P'P'/P and P'P'/PP were used in the same way as described for PKKP to calculate the corresponding values of A for P'P' (see Fig. 9). Special pains were taken to find P'P' for distances less than 50°. Since P' is a fairly strong phase between 155° to at least 175° [DENSON, in press] and since at an angle of incidence at the surface of less than 20° practically all the energy should be reflected into the longitudinal wave [GUTENBERG, 1944, Fig. 3c], P'P' should be recorded with amplitudes observable in shocks of major earthquakes at the corresponding distances from 50° (360°-310°) down to at least 10°. However, at the Southern

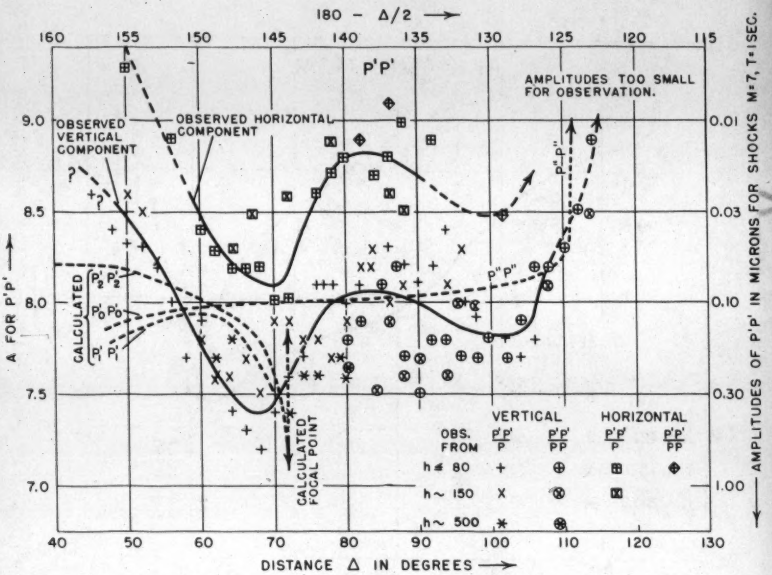


Fig. 9--A = M - log (a/T) for P'P' and corresponding amplitudes a in microns for waves having a period T of one second in a shock of magnitude M = 7.0

California stations, no P'P' waves could be identified beyond doubt in seismograms from shocks distant less than 45°; between 45° and 50° the observed amplitudes are very small (see Fig. 6). Unfortunately, at distances of less than 50° the many after-shocks usually recorded following major earthquakes render identification of PKKP at small distances doubtful, while in shocks with magnitude less than seven the amplitudes of P'P' to be expected are not larger than the usual microseisms. Records of large, deep shocks offer the best chance to observe P'P' at short distances. Consequently, seismograms of such shocks recorded at Huancayo, Peru (seismograms stored at Pasadena by courtesy of the Carnegie Institution of Washington) were examined. Unfortunately, the magnification of the long-period Benioff seismograph there was relatively low for the waves involved. In about ten instances (Δ = 14°-36°, h = 50-620 km) P'P' was identified with some doubt, and A was found to be probably greater than 7 1/2 to 7 3/4; in one instance with more definite indication of P'P' (Δ = 21°, h = 110 km) A was found to be about 7 3/4.

Combining all data mentioned we may conclude that at distances of less than 50° the value of A for the vertical component of the branch of P'P' with the largest amplitudes is at least eight. Beyond Δ = 50°, the amplitudes of P'P' increase rather rapidly with distance. The value of A for the horizontal component in Figure 9 is larger by about 0.6 or 0.7 (factor of about 1/4 in the amplitude) in agreement with the theory. Both curves for A reach a minimum (maximum of relative amplitudes, see scale at right of Fig. 9) near Δ = 70°. This corresponds to the main focal point of P' near Δ = 145°; distances for P' corresponding to those for P'P' are given above the figure. With increasing Δ the amplitudes decrease (A increases); they change relatively little between 80° and 110°. Beyond 110° the amplitudes decrease rapidly below the minimum necessary for observation (compare Fig. 7). This corresponds to the decrease in amplitudes of P', as the distance becomes smaller than about 125° [DENSON, in press] (see also Fig. 10).

The time interval PKKP-P depends little on focal depth [GUTENBERG and RICHTER, 1936, p. 358]. At the distances and focal depths which are involved the difference should rarely exceed

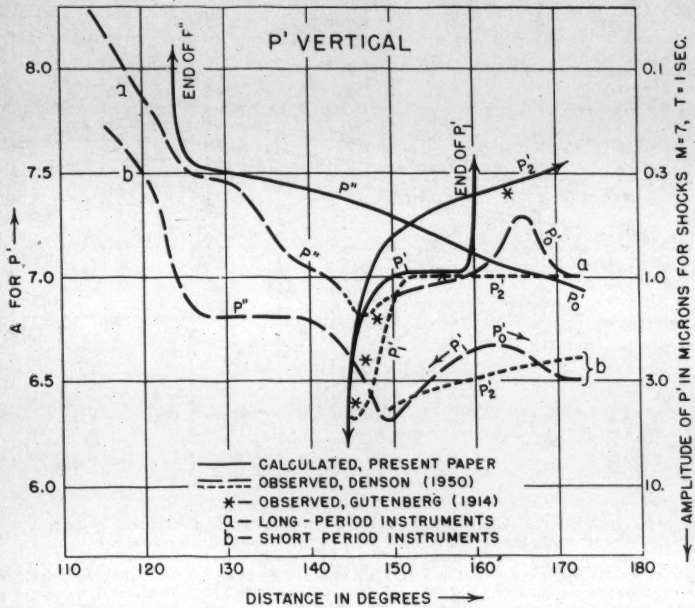


Fig. 10--A = M - log (a/T) for vertical component of P' and corresponding amplitudes a in microns for waves with a period T of one second in a shock of magnitude M = 7.0

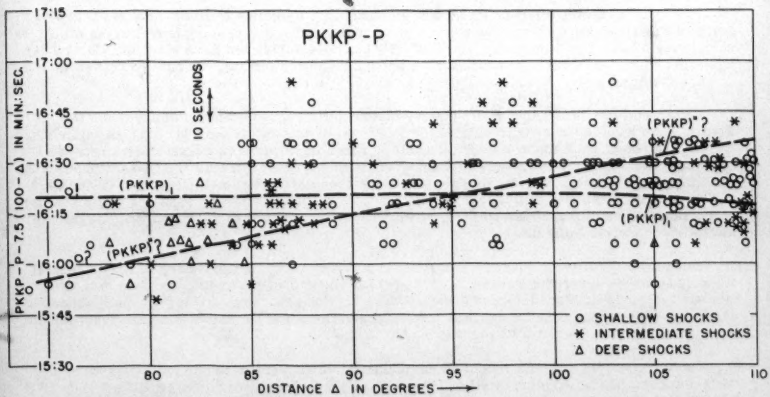


Fig. 11--Observed time intervals PKKP-P (usually read to the nearest tenth of one minute; the quantity PKKP-P-7.5 (100-Δ) has been plotted to permit the use of a larger time scale

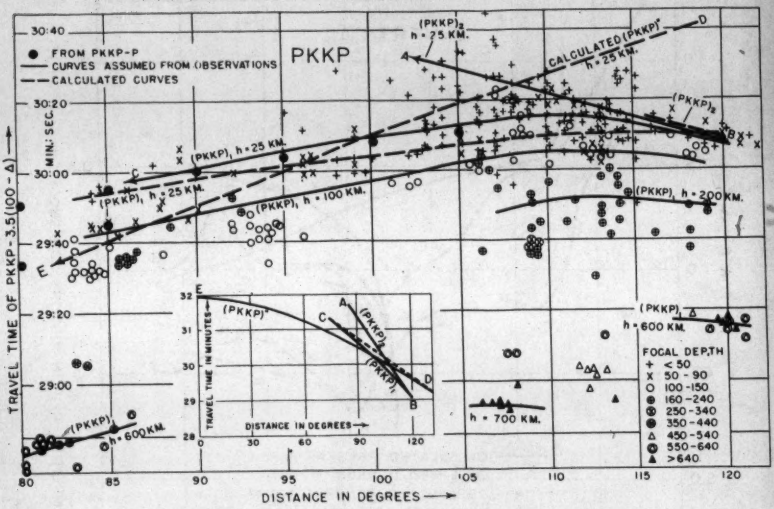


Fig. 12--Observed travel times of PKKP minus 3.5 (100-Δ) where Δ = distance in degrees, h = focal depth; insert: travel-time curve of PKKP for shallow earthquakes

three seconds. This is confirmed by Figure 11, in which the observed time differences are plotted against distance; the quantity 7.5 (100° - Δ°) is subtracted from PKKP-P to permit the use of a larger time scale. At distances less than about 95° (PKKP)'' seems to precede $(PKKP)_1$, at greater distances $(PKKP)_1$ arrives earlier. The relatively small time difference between the two curves renders difficult any distinction between the two branches.

In Figure 12 travel times of PKKP are plotted, using Pasadena Bulletin data as well as values found in Figure 11 for distances up to 105° after adding the corresponding travel times for P. To permit use of a larger time scale, 3.5 (100°-Δ°) has been subtracted from all data. Curves representing observed travel times for various depths have been plotted. Calculated curves will be discussed later.

Observed time differences P'P'-P were plotted (not reproduced here) in a way similar to Figure 11. Figure 3 shows travel times for P'P'. At distances beyond 100° a phase with characteristics different from those of P'P', especially with longer periods, occasionally precedes P'P' by a time interval which increases rather rapidly with distance. Plotting the travel times (at the right in Fig. 3) left no doubt that this phase is PPP over the greater arc (angular distance over 180°). In agreement with theoretical calculations, the amplitudes of this phase near Δ = 100° are of the same order of magnitude as those of PKKP. The difference in the appearance of the two waves is probably significant.

Since time differences PKKP-P and P'P'-P are very useful in the finding of the epicentral distance from seismograms written by short-period vertical instruments, pertinent data are tabulated in Table 2. For distances greater than 100°, the beginning of P is frequently found earlier on long-period than on short-period instruments so that the actual time intervals for these distances are greater than those given in Table 2.

Table 3 gives the travel times of PKKP and P'P' which were assumed for waves from a surface focus. These values as well as travel times for P' [partly from GUTENBERG and RICHTER, 1939, p. 115; partly from DENSON, in press] and for SKS [GUTENBERG and RICHTER, 1939, p. 118] were combined with times for PcP and ScS in the construction of travel-time curves

Table 2--Time intervals observed on records of short-period vertical seismographs in shallow earthquakes

Δ	P'P'-P	Δ	PKKP-P	P'P'-P	Δ	PKKP-P	P'P'-P	Δ	PKKP-P'	P'P'-P'
°	m s	°	m s	m s	°	m s	m s	°	m s	m s
48	31 13	70	.....	28 02	92	17 22	25 28	104	11 52	20 22
50	30 56	72	.....	27 48	94	17 09	25 15	106	11 43	20 11
52	30 38	74	.....	27 40	96	16 55	25 02	108	11 32	20 01
54	30 21	76	19 11	27 27	98	16 40	24 50	110	11 18	19 51
56	30 04	78	18 57	27 03	100	16 23	24 36	112	11 04	19 39
58	29 46	80	18 44	26 48	102	16 10	24 22	114	10 50	19 29
60	29 28	82	18 31	26 34	104	15 56	24 08	116	10 35	19 19
62	29 12	84	18 17	26 21	106	15 40	23 53	118	10 21	19 09
64	28 55	86	18 04	26 07	108	15 23	23 38	120	10 06	18 59
66	28 37	88	17 50	25 54	110	15 06	23 19	122	9 51	18 49
68	28 20	90	17 37	25 41	112	14 49	23 01	124	9 37	18 39
					114	14 31	22 43	126	9 21	18 30

P'P'-P decreases by about 2 1/2 seconds per 100 km increase in focal depth at Δ = 48°, by about 2 seconds at Δ = 64°, by about 1 1/2 seconds at Δ = 70°, and by about 1 second at distances greater than 72°. The effect of focal depth on the other time intervals is negligible in the preliminary interpretation of records.

Table 3--Assumed travel times of PKKP and P'P' for surface focus

PKKP				P''P'' and $P_0'P_0'$			
Δ	t	Δ	t	Δ	t	Δ	t
°	m s	°	m s	°	m s	°	m s
76	31 12	108	29 48	54	39 39	92	38 44
78	31 08	110	29 42	56	39 38	94	38 40
80	31 03	112	29 34	58	39 36	96	38 36
82	30 59	114	29 27	60	39 34	98	38 32
84	30 54	116	29 19	62	39 31	100	38 29
86	30 49	118	29 10	64	39 28	102	38 25
88	30 44	120	29 02	66	39 25	104	38 20
90	30 39	115	29 25	68	39 22	106	38 15
92	30 34	110	29 49	70	39 19	108	38 11
94	30 28	105	30 13	72	39 16	110	38 07
				74	39 14		
96	30 22	(PKKP)''				$P_1'P_1'$	
98	30 16			76	39 11		
100	30 11	80	30 47?	78	39 08	60	39 49
		85	30 42?	80	39 05	62	39 43
102	30 05	90	30 36?	82	39 02	64	39 37
104	29 59						
106	29 54			84	38 58	66	39 31
				86	38 55	68	39 25
				88	38 51	70	39 20
				90	38 48	71	39 17

for K (waves between points at the surface of the core) by the method described earlier in this paper. The data for PcP and ScS were based on GUTENBERG and RICHTER [1939, pp. 105-106]. The main part of the resulting calculated travel-time curve is plotted in Figure 2.

Figure 2 confirms the results of GUTENBERG and RICHTER [1938, 1939] and of JEFFREYS [1939] that the travel-time curve of K consists at least of two branches. The beginning of the

first branch (Δ between 0° and about 30°) is not known as accurately as the rest of the curve, since there are no waves with well-established travel-time curves which have their deepest point in the uppermost layers of the core. Well-determined times of SKS for epicentral distances less than 80° would give this information, but there SKS is preceded too closely by S to provide an accurate travel-time curve. However, SKS at distances beyond 80° furnishes valuable data for the first branch of the travel-time curve of K beyond $\Delta = 30°$. For distances beyond 90° the data for K based on SKS need revision, especially near $\Delta = 120°$, where the two branches intersect. The corresponding part of the travel-time curve of SKS has usually been smoothed to one continuous curve while theoretically two branches are to be expected intersecting each other in the neighborhood of $\Delta = 140°$

From $\Delta = 90°$ on, the curve for K is also indicated by data based on PKKP, and near $\Delta = 110°$ by data based on P′ and P′P′ also. The end of the first branch of K (A on Fig. 2) is given by the fact that PKKP decreases suddenly with decreasing Δ near $\Delta = 75°$. The decrease in amplitudes of P_1' near $\Delta = 160°$, observed by DENSON [in press] corresponds approximately to the same point.

From A a reversed segment is to be expected towards B or C, possibly corresponding to waves reflected at the inner core. Since this segment follows the second branch of K after a few seconds, and since a similar relationship exists between the corresponding branches in all observed types of waves through the core, no data can be expected to establish this reversed branch from observed travel times. For calculations of velocities by the usual integration its form and location must be estimated. For a discussion of this problem, see JEFFREYS [1939, p. 558] or BULLEN [1945].

Amplitudes of P′ as well as of P′P′ indicate that the second branch of the travel-time curve of K begins near $\Delta = 100°$. This point B corresponds to the end of observable P″P″ waves near 110°, and to the beginning of larger P″ waves near 125° observed by DENSON [in press], who also pointed out the noticeable change in observed periods of P″ at this distance. At shorter distances, P″ is small and usually shows waves with periods of no more than two seconds, thus contrasting with the long-period waves in the diffracted P at the same distances. From these observations as well as Jeffreys' theoretical result it seems unlikely that the segment CB, Fig. 2, corresponds to diffracted waves, although diffracted energy may be expected close to B. The corresponding waves are probably reflected at the inner core. The scattering of time observations of P″ at distances less than 124° does not permit us at present to determine the direction of curvature of the travel-time curve. The observed travel times of GUTENBERG and RICHTER [1934a, Table 10] indicate a slight reversal of curvature of their curve 3 for P″ near $\Delta = 118°$, but the other curves listed in Table 10 do not show this reversal, and the curves plotted [GUTENBERG and RICHTER, 1934a, Fig. 5, p. 89] are practically straight lines as far as about $\Delta = 116°$. The authors reported [p. 91], "It is possible that some of the P′-curves, especially 4, can be traced back across the PP curves as nearly straight lines."

The last branch of the travel-time curve of K, from B to greater distances, is given by observations of P″ (called P_0' beyond $\Delta = 143°$) and P′P′; beyond $\Delta = 125°$ data from SKS are added. Somewhat uncertain data from $(PKKP)_1$ agree in general.

While the absolute travel times of K seem to be known within five seconds or better, some more data on the points A and B and the direction of the curve near these points are still desirable. A revision of travel times and a study of amplitudes of other phases through the core, especially of SKS, SKP, SKPP′, is intended for the near future and is expected to improve further the travel-time curve of K.

The data now available can be used to calculate the amplitudes of the waves through the core by means of (3) or (4). P′ loses relatively little energy in passing through the core boundary. For all rays to be considered, 0.5 log F is between 0.0 and about −0.3, including the probable effect of the discontinuities in the Earth's crust. The term corresponding to the absorption is probable about 0.3 for all P′-waves [see DENSON, 1950]. The last term is the only one which depends noticeably on the distance. Its calculation offers no difficulty, but is somewhat uncertain at distances where the slope of the travel-time curve involved is in doubt. Figure 10 shows calculated curves for the quantity A and amplitudes of P′ together with curves for the average values observed by Denson. At the beginning of P″ near $\Delta = 125°$ the long-period instruments give about the expected amplitudes, but short-period amplitudes are about six times too large. Denson has found that the use of short-period waves of P′ results in earthquake magnitudes which are at least 0.5 greater than those calculated from long-period waves, if the same value for A is taken. This is not the case for P, PP, or S. The assumption that the energy spectrum for waves through the

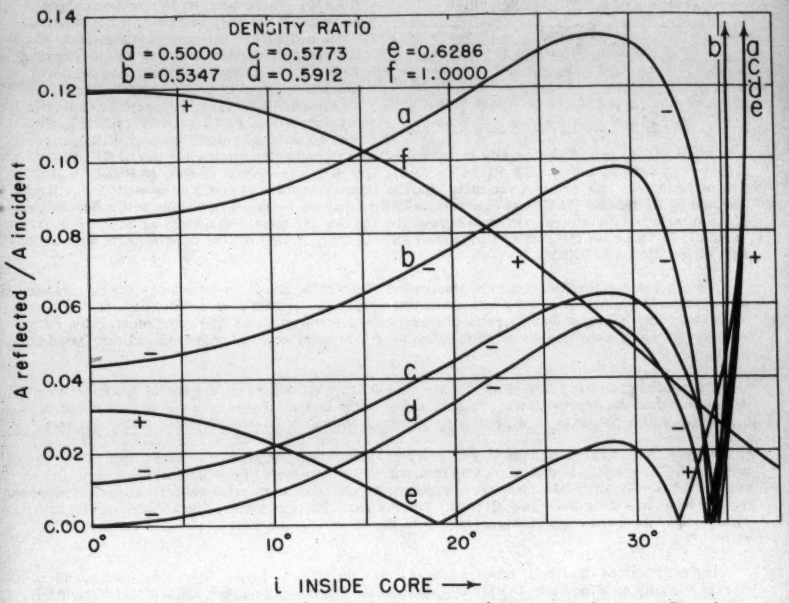


Fig. 13--Ratio of amplitudes (or square root of energy) of waves in the core reflected at the boundary of the core to the amplitudes of the incident waves; i = angle of incidence inside the core at its boundary

core is the same as that for waves through the mantle only is apparently not correct, and different constant terms in (3) should be used.

The main focal point of P' is clearly indicated by the data of DENSON [in press] as well as by A-values calculated by use of (5) from measurements of PP/P' by GUTENBERG [1914, Fig. 3] on records of relatively long-period instruments at Göttingen. For greater distances the observed amplitudes of long-period waves agree well with the calculated values, while amplitudes of P_0' found from the short-period instruments for distances near 160° are too large by about a factor two or three. For P_2' the difference is even greater. Since PcP is also rather too large than too small [MARTNER, 1950; ERGIN, in press] it seems that in the phases through the core some of the energy contained in long-period P-waves through the mantle is transferred to waves with shorter periods.

In calculations of A for PKKP the result depends very delicately on the density ratio at the boundary of the core. Figure 13 gives the ratio of the reflected to the incident amplitude (or, in this case, the square root of the corresponding energies) for longitudinal waves reflected inside the core. Curve b was calculated by DANA [1945]; Curve f by KNOTT [1919]; the others were added by the author. (Knott assumed that neither the density nor the bulk modulus changes at the core boundary but that the rigidity inside the core is negligible.) The assumed ratios of the densities are given in Figure 13. The wave velocities determine mainly the critical angle for which the ratio is unity and which corresponds to rays grazing the core. The values shown in Table 4 were assumed. The sign of the ratio indicates whether the phase is changed at the reflection (+) or not (-). Curve d corresponds to the condition that the product of density and longitudinal velocity is the same on both sides [compare GUTENBERG, 1944, Eq. 10, p. 88, for c = 0]. Since

Table 4--Assumed wave velocities

Curve	Longitudinal		Transverse
	Outside	Inside	Outside
	km/sec	km/sec	km/sec
a, c, d, e	13.70	8.10	7.30
b	13.70	8.00	7.25
f	12.89	10.15	6.88

$(PKKP)_1$ (corresponding to i between about 20° and 33°) is well observed, while observations of (PKKP)'' are practically missing for epicentral distances less than 75° (i less than about 10°) it follows that the assumption on which e is based is probably not a good approximation; e corresponds approximately to hypothesis II of BULLEN [1947, p. 218]. For the calculation of amplitudes of PKKP, curve c in Figure 13 was used; the density ratio of 0.57 corresponds about to the results of BULLEN [1950] or hypothesis I of BULLEN [1947, p. 218]. Curve b corresponds roughly to BULLEN [1936]. The other factors in F are close to unity, and the absorption term is probably close to 0.5. Recent findings by ELSASSER [1951] indicate the possibility that the increase in density in the deeper part of the mantle is greater than assumed heretofore and that the change in density at the core boundary is small. In this case the curve f in Figure 13 would apply, which is also in agreement with the observed amplitudes of PKKP.

Figure 8 shows that the observed amplitudes of $(PKKP)_1$ are about four times the calculated (the calculated quantity A is 0.6 greater than the observed). A part of this difference could be removed by taking a larger density ratio (for example, 0.5, curve a in Fig. 13) but most of the difference has probably the same cause as the similar discrepancy between observed and calculated amplitudes of P'

Calculated values for A in (PKKP)'' are near 9 1/2, indicating that in general (PKKP)'' should be smaller than the microseisms. This agrees with the lack of observations of (PKKP)'' and is partly due to the last term in (4), partly to the small amount of energy reflected inside the core.

Finally, A was calculated for P'P'. The first three terms in (4) range from about 6.7 (P''P'', $\Delta = 0$) to 7.2 ($P_2'P_2'$). For distances up to about 50° P'P' seems to be much smaller than it should be theoretically. The fact that it seems to be also too small relative to P' at the corresponding distances has been discussed already. For the rest, the agreement is as good as can be expected. The observed ratio of the horizontal to the vertical component is close to the theoretical ratio.

Table 5 contains the finally adopted travel times through the core. They were used to calculate the velocity as a function of depth by means of the Herglotz-Wiechert method as extended by

Table 5--Assumed travel times t and reciprocals of apparent velocities (1/V) per degree for waves between points on the surface of the core (the values referring to different branches of the travel-time curve are separated by horizontal lines)

Δ	t	1/V̄	Δ	t	1/V̄	Δ	t	1/V̄
°	m s		°	m s		°	m s	
5	0 37	7.5	85	8 40	4.2	105	10 13	1.83
10	1 15	7.4	90	9 01	4.1	110	10 22	1.77
15	1 52	7.4	95	9 21	3.9	115	10 30	1.72
20	2 29	7.3	100	9 40	3.6	120	10 39	1.67
25	3 06	7.2	105	9 59	3.3	125	10 47	1.62
30	3 42	7.1	110	10 14	3.0	130	10 55	1.55
35	4 17	6.9	115	10 28	2.8	135	11 03	1.45
40	4 51	6.7	120	10 42	2.6	140	11 10	1.35
45	5 23	6.3	125	10 55	2.4	145	11 16	1.2
50	5 53	5.8	130	11 06	2.20	150	11 22	1.0
55	6 21	5.4	125	10 55	2.19	155	11 27	0.9
60	6 47	5.0	120	10 44	2.17	160	11 32	0.8
65	7 11	4.7	115	10 33	2.13	165	11 35	0.6
70	7 34	4.6	110	10 22	2.05	170	11 37	0.4
75	7 56	4.4	105	10 13	1.95	175	11 39	0.2
80	8 19	4.3	100	10 03	1.87	180	11 40	0.0

SLICHTER [1932]. For these calculations it does not matter whether the reversed segment (Δ = 130° to 100°) corresponds to "direct" or reflected waves. The resulting velocities as a function of depth are plotted in Figure 1. Calculations of the velocity were carried out for other travel-time curves for K which were assumed within the limits of the observed points in Figure 2, but all resulted in velocity curves of the same type; the resulting differences consisted of more gradual or sudden and slightly smaller or greater increase in velocity at a depth slightly below 5000 km. None of them gave a decrease in velocity nor a strictly vertical segment. The form of the new curve is not unreasonable considering the high pressure at the boundary of the inner core. More detailed calculations concerning the possible forms of the reversed segment (AB in Fig. 2) may limit the assumptions which can be made concerning this segment, especially considering the possibility of reflected short-period waves.

Speculation about the cause producing the changes in velocity at the boundaries of the outer and the inner core is outside the scope of the present paper. For recent hypotheses on the Earth's core, see, for example, BROWN [1950], BULLEN [1950], COOPER [1950], ELSASSER [1950], and RAMSEY [1950], all of which give additional references. No hypothesis can be considered a good approximation which disagrees with the result that the boundary of the outer core is very sharp. Waves having lengths of ten km or even less are reflected at both sides of the boundary. The fact that PKKP has fair-sized amplitudes favors a ratio of at least 1 3/4 between the density inside and outside the outer core. No transverse waves of noticeable size have been observed to pass through the outer core, but at present there is no evident reason why transverse waves should not pass through the inner core.

References

ANGENHEISTER, G., Beobachtungen an pazifischen Beben, Nachr. Ges. Wiss. Göttingen, pp. 113-146, 1921.

BROWN, H., On the compositions and structures of the planets, Astrophys. J., v. 111, pp. 641-653, 1950.

BULLEN, K. E., The variation of density and the ellipticities of strata inside the earth, Mon. Not. R. Acad. Sci., Geophys. Sup., v. 3, pp. 395-401, 1936.

BULLEN, K. E., Features of the travel-time curves of seismic rays, Mon. Not. R. Acad. Sci., Geophys. Sup., v. 5, pp. 91-98, 1945.

BULLEN, K. E., An introduction to the theory of seismology, Cambridge Univ. Press, 1947.

BULLEN, K. E., An Earth model based on a compressibility-pressure hypothesis, Mon. Not. R. Acad. Sci., Geophys. Sup., v. 6, pp. 50-59, 1950.

COOPER, R. I. B., Internal constitution of the Earth, Nature, London, v. 165, pp. 216-219, 1950; see also The Observatory, v. 70, pp. 19-24, 1950.

DANA, S. W., The amplitudes of seismic waves reflected and refracted at the Earth's core, Ph. D. thesis, Calif. Inst. Tech., 1944, condensed in Bull. Seis. Soc. Amer., v. 35, pp. 27-35, 1945.

DENSON, M. E., Jr., Longitudinal waves through the Earth's core, Ph. D. thesis, Calif. Inst. Tech., 1950, condensed in Bull. Seis. Soc. Amer. (in press).

ELSASSER, W. M., The Earth's interior and geomagnetism, Rev. Mod. Phys., v. 22, pp. 1-35, 1950.

ELSASSER, W. M., Quantum theoretical densities of solids at extreme compression, Science, v. 113, pp. 105-107, 1951.

ERGIN, K., Amplitudes of PcP, PcS, ScS, and ScP in deep-focus earthquakes, Ph. D. thesis, Calif. Inst. Tech., 1950, condensed in Bull. Seis. Soc. Amer. (in press).

GUTENBERG, B., Ueber Erdbebenwellen VII A, Nachr. Ges. der Wiss. Göttingen, pp. 166-218, 1914.

GUTENBERG, B., Ueber den Erdkern in 2900 km Tiefe und die an ihm stattfindenden Reflexionen und Brechungen von Erdbebenwellen, Zs. angew. Geophysik, v. 1, pp. 105-115, 1925.

GUTENBERG, B., Energy ratio of reflected and refracted seismic waves, Bull. Seis. Soc. Amer., v. 34, pp. 85-102, 1944.

GUTENBERG, B., Amplitudes of P, PP, and S and magnitude of shallow earthquakes, Bull. Seis. Soc. Amer., v. 35, pp. 57-69, 1945a.

GUTENBERG, B., Magnitude determination for deep-focus earthquakes, Bull. Seis. Soc. Amer., v. 35, pp. 117-130, 1945b.

GUTENBERG, B., and C. F. RICHTER, On seismic waves (first paper), Gerlands Beitr. Geophysik., v. 43, pp. 56-133, 1934a.

GUTENBERG, B., and C. F. RICHTER, On P'P' and related waves, Gerlands Beitr. Geophysik., v. 41, pp. 149-169, 1934b.

GUTENBERG, B., and C. F. RICHTER, On seismic waves (second paper), Gerlands Beitr. Geophysik, v. 45, pp. 280-360, 1935.

GUTENBERG, B., and C. F. RICHTER, Materials for the study of deep-focus earthquakes, Bull. Seis. Soc. Amer., v. 26, pp. 341-390, 1936.

GUTENBERG, B., and C. F. RICHTER, P′ and the Earth's core, Mon. Not. R. Acad. Sci., Geophys. Sup., v. 4, pp. 363-372, 1938.
GUTENBERG, B., and C. F. RICHTER, On seismic waves (fourth paper), Gerlands Beitr. Geophysik, v. 54, pp. 94-136, 1939.
GUTENBERG, B., and C. F. RICHTER, Earthquake study in Southern California, 1947, Trans. Amer. Geophys. Union, v. 29, pp. 406-407, 1948.
GUTENBERG, B., and C. F. RICHTER, Seismicity of the Earth and associated phenomena, Princeton Univ. Press, 1949.
JEFFREYS, H., The times of the core waves, Mon. Not. R. Acad. Sci., Geophys. Sup., v. 4, pp. 548-561 and 594-615, 1939.
KNOTT, C. G., The propagation of earthquake waves through the Earth, and connected problems, Proc. R. Soc. Edinburgh, v. 39, pt. II, pp. 157-208, 1919.
LEHMANN, I., P′ as read from the records of the earthquake of June 16, 1929, Gerlands Beitr. Geophysik, v. 26, pp. 402-412, 1930.
LEHMANN, I., P′, Pub. Bureau Central Seismol. Internat., Trav. Sci., Ser. A, v. 14, pp. 87-115, 1936.
MACELWANE, J. B., The South Pacific earthquake of June 26, 1924, Gerlands Beitr. Geophysik, v. 28, pp. 165-227, 1930.
MARTNER, S. T., Observations of seismic waves reflected at the core boundary of the Earth, Ph. D. thesis, Calif. Inst. Tech., 1949, condensed in Bull. Seis. Soc. Amer., v. 40, pp. 95-109, 1950.
OLDHAM, R. D , The constitution of the Earth, as revealed by earthquakes, Q. J. Geol. Soc., London, v. 62, pp. 456-475, 1906.
RAMSEY, W. H., On the compressibility of the Earth, Mon. Not. R. Acad. Sci., Geophys. Sup., v. 6, pp. 42-49, 1950.
RUDOLPH, E., and S. SZIRTES, Ueber eine neue Laufzeitkurve (vorläufige Mitteilung), Phys. Zs., v. 15, pp. 737-739, 1914.
SLICHTER, L. B., The theory of the interpretation of seismic travel-time curves in horizontal structures, Physics, v. 3, pp. 273-294, 1932.
VISSER, S. W., On the distribution of earthquakes in the Netherlands East Indian Archipelago 1909-1919, Kon. Mag. Met. Obs., Batavia, Verhandelingen, no. 7, 77 pp., 1921.
WADATI, K., and K. MASUDA, On the travel time of earthquake waves, pt. 6, Geophys. Mag., Tokyo, v. 8, pp. 187-194, 1934.
WIECHERT, E., Ueber die Massenverteilung im Innern der Erde, Nachr. Ges. Wiss. Göttingen, pp. 221-243, 1897.
WIECHERT, E., Die Erdbebenforschung, ihre Hilfsmittel und ihre Resultate für die Geophysik, Phys. Zs., v. 9, pp. 36-47, 1908.
WIECHERT, E., and K. ZOEPPRITZ, Ueber Erdbebenwellen, Nachr. Ges. Wiss. Göttingen, pp. 415-549, 1907.
ZOEPPRITZ, K., Ueber die Amplitude der sogenannten ersten Verläufer in Erdbebendiagrammen und über einige Beobachtungen an Erdbebenwellen, Nachr. Ges. Wiss. Göttingen, pp. 123-143, 1912.

Seismological Laboratory,
220 North San Rafael Avenue,
Pasadena 2, California

(Communicated manuscript received September 11, 1950;
open for formal discussion until November 1, 1951.)

Transactions, American Geophysical Union Volume 32, Number 3 June 1951

ON THE ENERGY BALANCE OF THE ATMOSPHERE

Robert M. White

Abstract--The net radiative energy surplus or deficit of the atmosphere in middle and high latitudes is inferred from a consideration of energy transport processes in the atmosphere. It is shown that the results are consistent with estimates made through direct consideration of the radiative processes, thus providing an independent check upon them.

Introduction--Information concerning the radiation balance of the atmosphere may be obtained indirectly through procedures which do not involve measurement of the radiative processes themselves. Such determinations provide an independent estimate of the net radiative energy surplus or deficit within given regions of the atmosphere. The orders of magnitude of the radiative surplus or deficit derived in this manner for the mid-latitude and polar regions are shown to agree favorably with other measurements of this quantity which are available from direct consideration of the radiative processes.

The formulation of the problem--The problem may be described in the following manner. In the Earth's atmosphere, a poleward flux of total energy in all forms is necessitated by the unequal net heating of equatorial and polar regions in the presence of a mean hemispherical temperature distribution which remains relatively constant over long periods of time. Let us consider the entire volume of the atmosphere which is contained between two latitudes forming the equatorial belt between $+\phi$ and $-\phi$. Over long time periods the sole source of energy for this region of the atmosphere is the solar energy which it receives from space by radiation. It is generally agreed that conduction of heat energy through the Earth's crust is unimportant for the present problem. A given amount of energy is also lost from this volume of the atmosphere by long-wave radiative processes. The difference between the amount of short-wave radiative energy which is received and the outgoing long-wave radiation results in a surplus for the equatorial belt of the atmosphere extending from approximately +45°N to -45°S. Poleward of these latitudes it is generally considered that there exists a net radiative energy deficit.

It is probable that the energy storage within the atmosphere, oceans, or solid earth, over time periods of the length which are considered here is quite small since there appears to be no progressive change of the temperature of the atmosphere, oceans, or solid earth during such periods. Some energy storage within the earth-atmosphere system may be possible during periods of increase or decrease of the polar ice caps. However, this effect should be quite small since the time periods being considered are much shorter than the time between marked changes in the extent of the ice cap. It is necessary, therefore, that the radiative energy surplus be transported out of equatorial regions into the regions of radiative energy deficit.

STARR [1951] has studied this problem recently and has formulated it in a convenient manner as follows

$$H = h + \int_s (C_p T + Lw + \Phi + c^2/2)\,\rho V ds \qquad (1)$$

where H is the net rate of external heat addition to the volume of air plus hydrosphere which in this case may be identified with the net effective radiation, h is the energy flux within the hydrosphere, C_p is the specific heat of air at constant pressure, T is the temperature, w is the specific humidity, L is the latent heat of water vapor which may be considered constant in this instance, Φ is the potential energy per unit mass of air, ρ is the density, c is the total vector particle velocity, V is the meridional component of velocity considered positive when the wind is from the south, and ds is an element of the conical surface erected at latitudes $\pm\phi$ and the integration is to be performed over the entire surface. This equation can be inferred directly from general considerations. However, the reader is referred to STARR [1951] for a better development of this equation from the general physical energy equation and the equations of motion. The interpretation of this equation is quite simple. It states that the total flux of energy which must be directed from equator to pole may be considered to be comprised of a flux of (a) sensible heat ($\int_s C_p T \rho V ds$), (b) latent energy of

water vapor ($\int_S Lw\rho V ds$), (c) kinetic energy ($\int_S (\rho c^2/2)\, V ds$), (d) potential energy ($\int_S \Phi\rho V ds$), and (e) a contribution due to the poleward transport of energy by the oceans (h). Thus it becomes theoretically possible to arrive at estimates of the net radiative energy surplus within given latitude belts in the atmosphere by measuring the terms on the right-hand side of (1). This method of approach has not been feasible until very recent years in view of our inability to measure the terms on a hemispherical basis with sufficient accuracy. However, with an expanded network of observing stations it has now become possible to make a preliminary attempt at measuring them.

A very real question arises when attempts are made to measure the meridional flux of energy in its various forms. This question stems from the nature of one's approach to the mode of operation of the general circulation. If it is supposed that the energy exchanges of the atmosphere are accomplished by the large-scale horizontal eddy motions, such as those associated with eddies the size of cyclones and anticyclones, then it becomes feasible to measure the magnitudes of the terms in (1) from hemispherical maps of standard meteorological quantities. If, on the other hand, it is supposed that the principal mode of energy exchange is accomplished through a process which in the main depends upon the existence of significant meridional cells operating in meridional planes so that the energy exchange process is essentially a vertical mass exchange process, then the problem becomes one of infinite complexity and difficult to compute from currently available data because of our inability to measure the magnitude of such cells. In the case of the energy-exchange process it is felt that the large-scale horizontal eddy exchange processes are the dominant ones. In what follows this assumption will be made.

The energy transport within the oceans--A certain amount of the total energy transport is accomplished by the currents of the oceans. In meteorology it is generally assumed that the transport of energy by ocean currents as internal energy of the water is quite small. SVERDRUP [1942] points out that this question has never been thoroughly examined principally because of lack of data. However, he agrees that when dealing with averages for the entire Earth this assumption is essentially correct. In localized areas, however, Sverdrup points out that the contribution of the ocean currents to the total energy transport may be as large as ten per cent of the total transport. These regions are thought to occur principally in middle latitudes where the principal north-south branches of the ocean currents are found. He also points out that in the southern oceans the north-south circulations and the corresponding temperature contrasts between currents flowing meridionally are very small. In view of this it seems that no great error will be introduced if the transport of energy by ocean currents is neglected in what follows, since great accuracy in the overall picture cannot in any case be expected.

The transport of existing kinetic energy--It is generally accepted [STARR, 1949] and it can be shown observationally, as has been done by the author in an unpublished doctoral thesis, that the transfer of existing kinetic energy is about two orders of magnitude smaller than the meridional transfer of energy as sensible heat and may be safely neglected in comparison with it.

The potential-energy transport--Since we have under consideration only horizontal eddy exchange processes it is obvious that there can be no transport of energy in this form since the geopotential is constant at any given elevation.

We thus arrive at the result that probably the energy-exchange processes in the atmosphere may be considered to be largely comprised of a transport of sensible heat and a transport of latent energy. This is fortunate since it is possible to arrive at estimates of the hemispherical transport of these quantities.

The latent-energy transport--The latent-energy transport may be evaluated in several ways. One approach is to use the observed moisture and wind data which are available from radiosonde and radio wind observations. The horizontal eddy transport of latent energy may then be obtained from such data. PRIESTLEY [1949] has suggested a method for utilizing such data and computed the latent energy transport for one station, Larkhill, England, for a period of two years. Using a method similar to Priestley's, WHITE [1951a] has obtained a measure of the latent-energy transport for one summer month and one winter month for a large number of stations extending from the tropics to the poles over the North American sector of the hemisphere. Although it is possible to use these rough estimates of the latent-energy transport obtained in this fashion, they suffer the serious drawback that they have been obtained from very restricted regions of the hemisphere for short time periods.

A second approach and one which is favored in this case is the computation of the long-term mean transport of latent energy from hemispherical evaporation and precipitation data. Over long

periods of time it may be assumed that there is no net change in the moisture of the atmosphere. If, therefore, there exists an excess of evaporation over precipitation within a given latitude belt in the atmosphere, there must exist over long time periods a transport of moisture and hence of latent energy out of the region. On the other hand, when the precipitation exceeds the evaporation, there must exist a transport of moisture into this latitude belt. Use of this indirect method of determining the flux of latent energy into given regions of the atmosphere does not assume that the transport of latent energy is accomplished solely by horizontal processes.

The knowledge of the net rate of evaporation from the land surfaces is extremely uncertain. However, it is possible to arrive at some estimates of the difference between precipitation and evaporation over large areas by a consideration of the amount of water discharged by the rivers into the oceans. Over a long period of time the difference between the precipitation and evaporation must equal the amount of water which is discharged into the oceans by the rivers. Such a treatment is valid only when long time periods are considered because a knowledge of the storage capacity of the ground is necessary and must be taken into account over short time periods. Such river-discharge data are available over wide areas of the land surface of the hemisphere. WUST [1922] has made use of them in computing the difference between the precipitation and evaporation over land surfaces.

Wust has also made estimates of the difference between the evaporation and precipitation over the ocean areas of the hemisphere. He used widely scattered pan observations of evaporation over the oceans and the precipitation data available from island stations. Since the evaporation data from the oceans are more reliable than over the land areas it is felt that such estimates represent a fairly good first approximation to actual conditions.

CONRAD [1936] has extended Wust's data to include the entire surface of the Earth and has estimated the latitudinal distribution of the net evaporation. Over long periods of time we may consider that there is no progressive change in the moisture content of the atmosphere although it is realized that over geological epochs there is some evidence of such changes.

From continuity considerations, by treating first the regions around the pole, it is possible to obtain a measure of the transport of moisture which must exist into the various latitude belts of the atmosphere. The values of these transports are given in Table 1. It is the opinion of Wust that his estimates are correct to within 15 pct.

Table 1--The observed meridional transport of latent energy and sensible heat

Latitude north	Latent energy	Sensible heat	Latent energy + sensible heat
°	(cal/sec) $\times 10^{12}$	(cal/sec) $\times 10^{12}$	(cal/sec) $\times 10^{12}$
75	+30	+14	+43
65	+99	+329	+428
55	+224	+834	+1058
45	+397	+793	+1189
35	+425	+355	+780

Note: Internal consistency subject to rounding off errors. Positive signs indicate a poleward transport.

The transport of sensible heat--Estimates of the horizontal eddy flux of sensible heat can be made (with considerable effort) directly from northern hemisphere weather charts of pressure and pressure-height contours. The transport of sensible heat across a complete latitude circle at a given elevation can be written as

$$\oint C_p T \rho V dx \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

where the integration is to be performed completely around the latitude circle and dx is an element of longitudinal distance. Because of the lack of direct wind observations over most of the hemisphere it becomes necessary to use a geostrophic measure of the wind given by the relation

$$V_g = (1/\rho f)\, \partial p/\partial x \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

where f is the coriolis parameter and p is the pressure. A reliable measure of the temperature may be obtained if it is realized that the mean virtual temperature of any column of air is directly proportional to the height difference between two constant pressure surfaces. The product of the

mean geostrophic wind for a given layer and the mean virtual temperature may be formed at a large number of evenly distributed points around a given latitude and the integral (2) may be evaluated by finite difference methods. Such computations were carried out by WHITE [1951b] for the four winter months, November 1945 - February 1946, on a daily basis for every ten degrees of latitude extending from 35°N to 75°N. The geostrophic transport of sensible heat was computed up to the 500-mb surface in two layers: Surface to 700 mb, and 700 mb to 500 mb. For details of these computations the reader is referred to the investigation mentioned previously.

By virtue of the fact that a geostrophic measure of the wind was used, transports of sensible heat which are accomplished by mean meridional cells are automatically eliminated since

$$\oint \rho V_g \, dx = \oint (1/f)\,(\partial p/\partial x)\, dx = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Use of the values of the geostrophic transport of sensible heat computed by White in conjunction with estimates of the normal latent-energy transport requires a certain amount of justification. In the first place, the estimates of the latent-energy transport evaluated from evaporation and precipitation data have been made on a yearly normal basis. The geostrophic transport of sensible heat was computed for four months of one winter season. In addition, the question may legitimately be raised as to the nature of the difference between the geostrophic and the actual eddy transports.

Studies of the eddy sensible heat transport over North America [WHITE, 1951b] have shown that there is good agreement (within 20 pct in the mean) between the eddy sensible heat flux computed geostrophically and that obtained from observed winds. The other question which must be answered is of a more serious nature. How closely does the eddy sensible heat transport computed up to 500 mb for the winter season represent the mean yearly transport through the entire atmosphere?

It appears that the transport computed up to 500 mb is smaller than the total eddy transport of sensible heat through the entire atmosphere since the transport of sensible heat above 500 mb has been neglected. On the other hand, there is a compensating factor in that the transport of sensible heat during the winter is greater than it is during the summer and hence use of the transports based upon winter data alone as a typical yearly value will be considerably in overestimate.

Studies of the extent to which these two factors actually cancel [WHITE, 1951a], based upon investigations of the eddy sensible heat transport over regions of North America in which observed wind and temperature data were used, show that the transports of sensible heat up to 500 mb represent approximately 70 pct of the total across a given latitude circle up to 100 mb. On the other hand, the winter-time rate of transport computed up to 500 mb is approximately 45 pct greater than the mean rate of transport.

In view of these results it seems permissible to use the geostrophic eddy sensible heat transport computed up to 500 mb for one winter season as a first approximation to a typical yearly mean transport. It must be remembered that the determination of a reliable normal for the magnitude of this term will require the analysis of many years of complete northern hemisphere data up to very high levels. Since the purpose at hand is merely to demonstrate the feasibility of this method of attack upon the radiation problem and to arrive at orders of magnitude, the use of these values is sufficient.

The mean winter geostrophic eddy sensible heat transport below 500 mb based upon the four winter months of data is presented in Table 1 together with the sum of the transport of energy as latent energy and sensible heat.

With the data of Table 1 it is possible to determine the net radiative energy surplus or deficit within given latitude belts in the atmosphere and to compare them with similar estimates which have been made by considering the radiative processes. The procedure is quite simple. We find that 43 units (cal/sec $\times 10^{12}$) are transported across latitude 75°N. The region of the atmosphere bounded on the south by this latitude must therefore radiate an amount of energy equal to this amount back to space in excess of that which it receives from space, otherwise there would be a progressive increase in the temperature of the atmosphere in this region. We may proceed in a similar fashion to the latitude belt 65°N - 75°N. Here we find 428 units transported in from the south, 43 units transported out to the north, and hence a surplus of 385 units of energy transported into this region. This amount must therefore represent the excess long-wave radiation by the atmosphere over the short-wave radiation which it receives from space. We may thus arrive

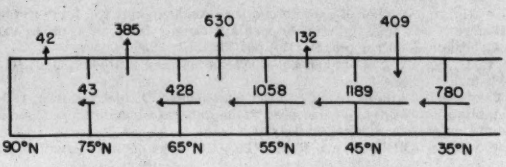


Fig. 1--Schematic diagram of the radiation balance deduced from observed energy transports; units in 10^{12} × cal/sec; direction of arrows indicates direction of flux; internal consistency subject to rounding-off of errors

Table 2--Radiative energy surplus or deficit within various latitude belts as determined from radiative processes by various investigators and from observed atmospheric energy transports in this study

Latitude north		Albrecht	Houghton	Gabites	White
From	To	(cal/sec) × 10^{12}	(cal/sec) × 10^{12}	(cal/sec) × 10^{12}	(cal/sec) × 10^{12}
°	°				
75	90	-126	-319	-222	- 43
65	75	-173	-392	-298	-385
55	65	-182	-405	-284	-630
45	55	-130	-322	-202	-132
35	45	- 3	-129	+ 29	+409

Note: Positive signs indicate a net surplus; negative signs a net deficit.

at an energy continuity diagram such as depicted in Figure 1. Here the amount of net radiative unbalance for each latitude belt is represented by the vertical arrows at the top of the diagram and the horizontal transport within the atmosphere by the horizontal arrows.

Comparison of results--It is of interest to compare the results of the computations described above with those of other investigators who have attacked this problem through a consideration of the radiative processes. Since the energy-transport data were available only for middle and polar latitudes, the discussion will be confined to these regions. Of the many investigations into this problem three have been selected for comparison, that of Albrecht and BJERKNES [1933, p. 665] and two of a more recent nature, that of Houghton (talk given at Cambridge Seminar of the American Meteorological Society, 1946) and that of Gabites (doctoral thesis, Massachusetts Institute of Technology, 1950). The results of Houghton's investigation should be considered as only preliminary in nature, as he is currently preparing a revised estimate. The values of the net radiative energy surplus or deficit reduced to the same units for the same regions which were used in this study are presented in Table 2, along with the results of the present investigation.

It is seen that the orders of magnitude of all these investigations are comparable, the more recent investigations agreeing more closely with the results of the present study. It is evident that the results of the present study give consistently higher values both for the net radiative deficit and the net radiative surplus except within the region between 75°N and the pole. This indicates that the intensity of the energy transport processes and the convergence of the energy transports are found to be more intense in the current study than would be indicated by the measurements based upon the radiative processes. It is also suggested that the region of net radiative heating in the atmosphere extends farther poleward than would be indicated by a consideration of the radiative processes. Nevertheless, it is quite gratifying, considering the crudity of the data which have been used to find that the estimates of the radiation balance deduced from radiative processes are fairly consistent with observations of the energy transport processes within the atmosphere. It appears that further studies of the energy transport processes might yield more reliable information which would provide an independent check upon the radiation balance as deduced from radiative processes. The desirability of further investigation is clearly indicated.

References

BJERKNES, V., and Collaborators, Physikalische Hydrodynamik, Verlag Julius Springer, Berlin, 1933.

CONRAD, V., Die klimatologischen Elemente und ihre Abhängigkeit von terrestrischen Einflussen in Handbuch der Klimatologie, Koppen and Geiger (Ed.), v. 1, pt. B, "Die Verdunstung," Verlag von Gebruder Borntraeger, Berlin, pp. 360-362, 1936.

PRIESTLEY, C. H. B., Heat transport and zonal stress between latitudes, Q. J. R. Met. Soc., v. 75, pp. 28-40, 1949.

STARR, V. P., Transport of kinetic energy in the atmosphere, J. Met., v. 6, p. 160, 1949.

STARR, V. P., Application of energy principles to the general circulation in Compendium of Meteorology, American Meteorological Society, 1951.

SVERDRUP, H. U., M. W. JOHNSON, and R. H. FLEMING, The oceans, Prentice-Hall, Inc., 1087 pp., 1942.

WHITE, R. M., The meridional eddy flux of energy, Q. J. R. Met. Soc., v. 75, 1951a.

WHITE, R. M., The meridional flux of sensible heat over the northern hemisphere, Tellus, v. 3, 1951b.

WUST, G , Verdunstung und Niederschlag auf der Erde, Zs. Ges. Erdkunde, v. 37, pp. 35-43, 1922.

Geophysical Research Directorate,
Air Force Cambridge Research Laboratories,
Cambridge, Massachusetts

(Communicated manuscript received January 23, 1951;
open for formal discussion until November 1, 1951.)

MAGNETIC ANOMALIES AT HIGH ALTITUDES

Isidore Zietz and Roland G. Henderson

(Published by permission of the Director, U. S. Geological Survey)

Abstract--To investigate the effect of anomalies in the Earth's magnetic field at high altitudes, aeromagnetic maps of two representative areas showing isanomalic curves for total intensity are projected to levels of 10 and 20 miles above the surface of a plane Earth. The projections are accomplished by numerical computations and by use of a magnetic-field projecting machine at the Naval Ordnance Laboratory. It is found that anomalies of 500 gammas near the surface of the Earth, in merging into neighboring anomalies, may produce effects of 100 gammas or more at an altitude of 20 miles.

Introduction--In studies of the Earth's magnetic field at great heights, the question of the effect of magnetic anomalies which arise from the Earth's crust has been given attention from several points of view. Simple calculations on the assumption that the anomaly is that of a dipole or point pole might give the order of magnitude of the effect, but such calculations are wholly inadequate for the quantitative information demanded by some types of research. As altitudes of 10 or 20 miles exceed the heights at which airborne magnetometer surveys are practicable, determinations must be made indirectly. A study by VESTINE and others [1947] shows how the grosser regional anomalies are affected by elevation, and it has been adequately shown that the more intense local anomalies must be somewhat more rapidly attenuated with altitude [MALKIN, 1935a and b; HOWE, 1940; MORELLI, 1945]. The work of SKEELS and WATSON [1949], PETERS [1949], the present authors [HENDERSON and ZIETZ, 1949b], and others demonstrates that the magnetic field at any level above the surface of the Earth can be computed from data obtained at a lower level. Moreover, the calculations neither involve assumptions as to the cause of the anomalies nor make any distinctions among them as to the nature of their decay. In this paper the magnetic fields in two representative areas are investigated and the extent of the persistence of magnetic anomalies at high altitudes is determined.

Data and processes--The U. S. Geological Survey and Naval Ordnance Laboratory undertook jointly the task of projecting the Earth's magnetic field observed over several areas to heights of 10 and 20 miles (16 and 32 km). The maps used (see Fig. 1 and 2) were based on aeromagnetic surveys flown 1000 ft (0.3 km) above sea level over the Clearfield-Philipsburg area in central Pennsylvania and the Naval Petroleum Reserve No. 4 in Alaska. The instrument used in the surveys was the saturable-core airborne magnetometer, AN/ASQ-3A, which measures variations in the total magnetic field.

To insure valid determinations, two methods were employed -- numerical computations and machine projection. The latter involves an instrument developed for use at the Naval Ordnance Laboratory. Extension by computation is described in an article by the authors [HENDERSON and ZIETZ, 1949b].

Computational method--Briefly, the computations are effected by obtaining averages of the field on circles of known radii centered at each point for which the field value is desired. These averages are multiplied by appropriate weights and the resulting products are summed to give the value at the point. The averages around circles are most easily obtained by superimposing a square grid over the area to be extended and interpolating to find the value of the field at the corners. In the process the following fundamental assumptions are made: That the Earth's surface in the area concerned may be approximated by a plane; that the normal field is invariant over the area; and that the magnitude of the anomalous field is small in comparison with the Earth's field.

Some of the data for Naval Petroleum Reserve No. 4 were thus projected to 10 and 20 miles above the level of observations. The results, which appear in the form of contour maps, are illustrated in Figures 3 and 4 respectively. Both figures indicate a merging of neighboring anomalies at high altitudes. Well-defined closed anomalies on the 1000-ft level are evident at the higher levels only as noses or broad bends in the contour lines. The Umiat anomaly of 500 gammas at 1000 ft has broadened considerably at ten miles and has diminished in amplitude to ap-

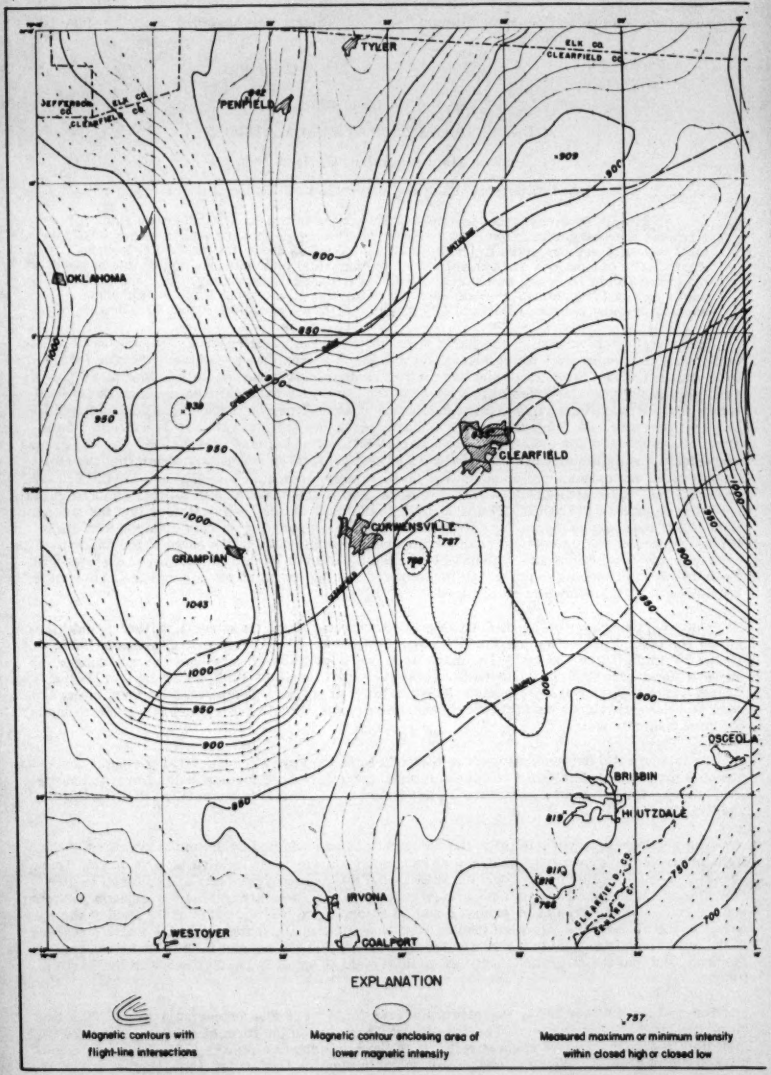


Fig. 1--Aeromagnetic map of Clearfield-Philipsburg area,

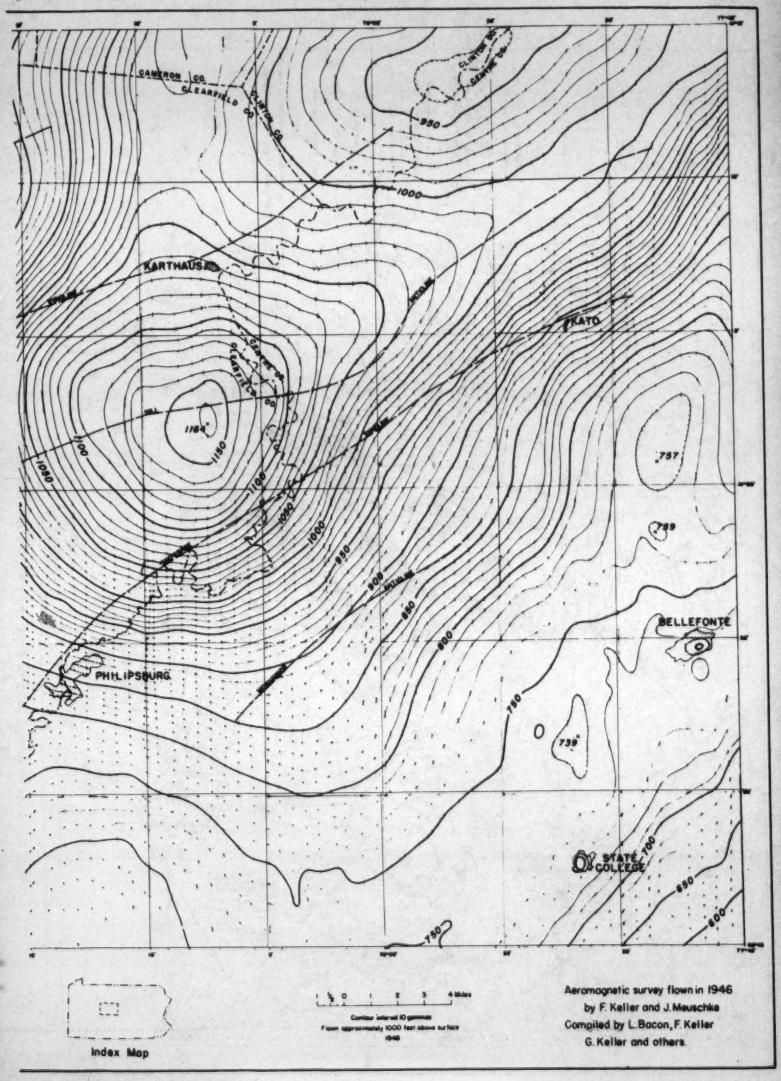

CAMERON CO.
CLEARFIELD CO.
CLINTON CO.
CENTRE CO.
KARTHAUS
KATO
PHILIPSBURG
BELLEFONTE
STATE COLLEGE
950
1000
1050
1100
1150
1200
1250
1300
1350
1400
1450
1500
1550
1600
1650
1700
1750
1800
1850
1900
1950
2000
2050
2100
2150
2200
2250
2300
2350
2400
2450
2500
2550
2600
2650
2700
2750
2800
2850
2900

Fig. 2--Aeromagnetic map of part of Naval Petroleum Reserve No. 4, Alaska

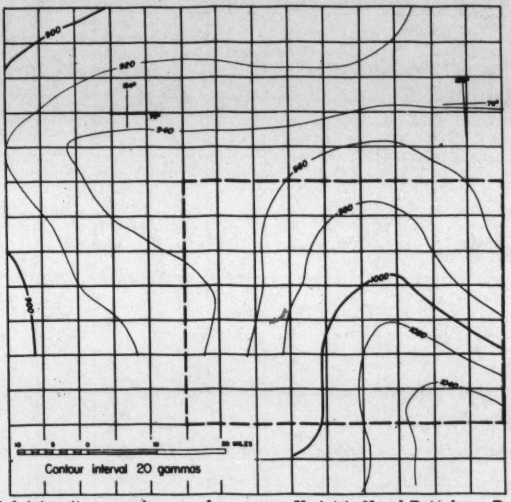


Fig. 3--Total-intensity anomaly map of area near Umiat in Naval Petroleum Reserve No. 4, Alaska, computed ten miles above plane of aeromagnetic observations

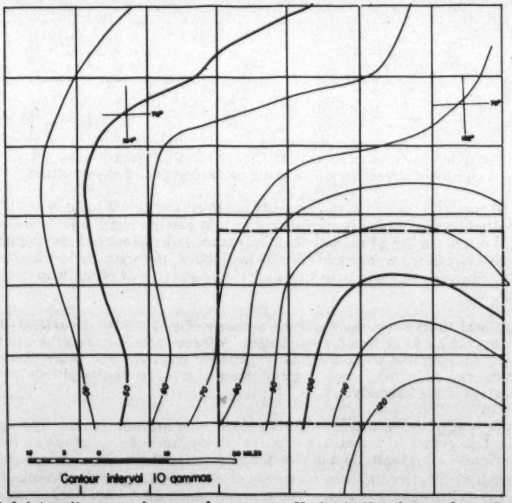


Fig. 4--Total-intensity anomaly map of area near Umiat in Naval Petroleum Reserve No. 4, Alaska, computed 20 miles above plane of aeromagnetic observations

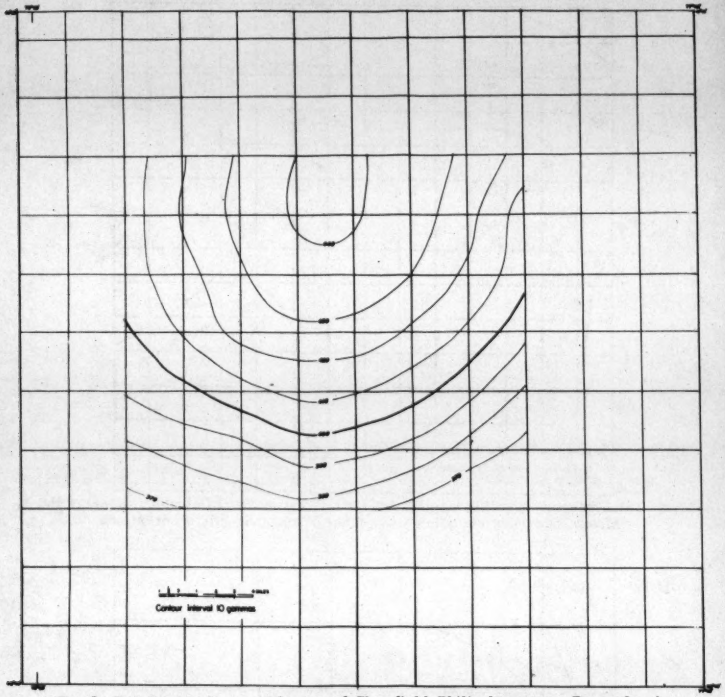


Fig. 5--Total-intensity anomaly map of Clearfield-Philipsburg area, Pennsylvania, computed ten miles above plane of aeromagnetic observations

proximately 150 gammas. Although the anomaly northwest of Umiat located at 69° 50′N and 154° 00′ W does not exhibit closures, nevertheless it is easily identifiable by a sharp change in gradient. At 20 miles the Umiat anomaly has decreased in gradient and the amplitude has been reduced to about 100 gammas. For the 20-mile projection, the anomaly to the northwest is still distinguishable. Because of inadequate coverage the southern half of the map could not be projected.

As an additional illustration the Karthaus anomaly (Fig. 1) in the Clearfield-Philipsburg area in central Pennsylvania was chosen for extension. A three-mile-square grid was used and the data were projected ten miles above the Earth's surface (Fig. 5). The same characteristic features are encountered as before, namely, a decrease in gradient and amplitude and an increase in the lateral extent of the anomaly.

The machine method--The magnetic-field projector, a machine originally employed by the Naval Ordnance Laboratory in its studies of ships' fields, served as a check on the computing method. The machine is essentially a device for simulating the vertical component of the magnetic field throughout a horizontal area by means of 800 closely spaced solenoids forming a rectangular array (40 rows of 20 coils). The plane in which the known field is reproduced is that of the lower ends of all the coils. Each coil is of rectangular cross section and may be connected to any desired tap of a transformer, thus setting up an electromotive force in the solenoid pro-

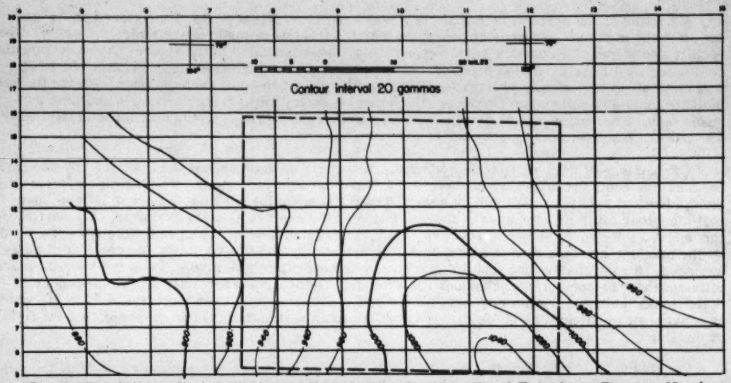


Fig. 6--Total-intensity anomaly map of area near Umiat in Naval Petroleum Reserve No. 4, Alaska, machine projected ten miles above plane of aeromagnetic observations

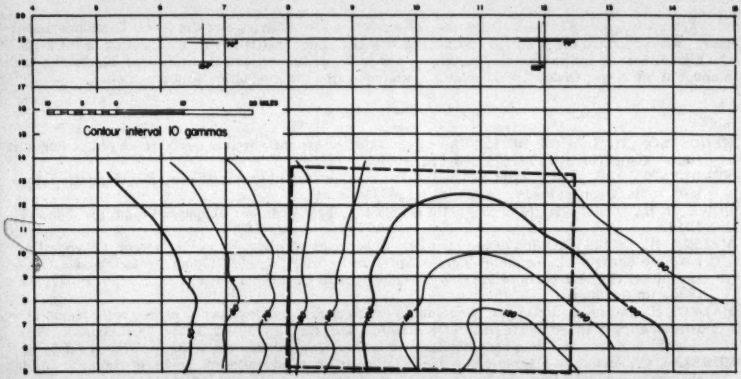


Fig. 7--Total-intensity anomaly map of area near Umiat in Naval Petroleum Reserve No. 4, Alaska, machine projected 20 miles above plane of aeromagnetic observations

portional to the observed magnetic field. The alternating magnetic field produced by the current in the solenoid induces an emf in a search coil mounted on a carriage that travels continuously in a horizontal line at a selected height. A recorder plots a continuous curve that is proportional to the emf induced in the coil and hence proportional to the magnetic field. By shifting the exploring device in a horizontal plane parallel to itself and by repeating the process there results a series of magnetic profiles for contouring. Three recorders are available for use, each picking up one of the three rectangular components of the field.

For this project, only the vertical-component search coil was used. In this manner the machine becomes a means for projecting vertically any potential whose distribution is known over a plane surface. The fact that the component of the total-intensity vector in the direction of the Earth's field satisfies the Laplace equation [HENDERSON and ZIETZ, 1949a] permits the use of the machine in this problem.

A portion of the aeromagnetic data of Naval Petroleum Reserve No. 4 mentioned above was set up in the machine, and projections of the Earth's field were made to the indicated levels. The results are shown in Figures 6 and 7 respectively. Also indicated in the figures is the rectangular grid selected for the extension process. In computing the grid dimensions the ratio of 55 to 20 was maintained to conform with the length-to-width ratio of the coil cross section. As the figures indicate, only 400 coils were employed, five coils on each profile being used for smoothing purposes only. The contours, which were based on west-east profiles, display a characteristic wave-like pattern that seems to be peculiar to the process.

Comparison of data using both methods--The computed data and the data obtained by use of the machine compare favorably for both the 10- and 20-mile elevations. To facilitate comparisons, identical areas are outlined by heavy dashed lines. On the average the error is less than half a contour interval. Because of the limitation of the number of coils available, only part of the desired field could be accurately projected. The dimensions of the area faithfully reproduced by the machine are less than the first-level dimensions by two to four times the vertical distance extended. It is probably true that the machine, when operating effectively, is on the average more efficient than the computing techniques for extending fields. However, only a limited number of coils is available and the dimensions of their cross sections must bear the ratio of 55 to 20, which is convenient in calculating ships' fields but is sometimes disadvantageous in projecting the field of the Earth.

Conclusion--It is evident that for the areas selected the projected anomalies, although smaller in amplitude, still appear at 10 and 20 miles above the Earth's surface. With sufficient flight coverage, some of these would probably exhibit closed highs. There is reason to believe that at high altitudes this anomalous condition will prevail in many other areas of the world.

Acknowledgments--The authors are indebted to L. R. Alldredge of the Naval Ordnance Laboratory, who proposed the problem and arranged N.O.L. cooperation; to H. R. Joesting of the U. S. Geological Survey for valuable suggestions; and to W. J. Dichtel and R. L. Knodle, electronic technicians at the Naval Ordnance Laboratory, who operated the magnetic-field machine.

References

HENDERSON, R. G., and I. ZIETZ, The computation of second vertical derivatives of geomagnetic fields, Geophysics, v. 14, pp. 508-516, 1949a.

HENDERSON, R. G., and I. ZIETZ, The upward continuation of anomalies in total magnetic intensity fields, Geophysics, v. 14, pp. 517-534, 1949b.

HOWE, H. HERBERT, Height of magnetic anomalies, Trans. Amer. Geophys. Union, pp. 309-311, 1940.

MALKIN, N., On the variation of the elements of terrestrial magnetism with height, Glavnoe Upravlenie Edinoĭ Gidro-meteorologicheskoĭ Sluzhby SSSR, Trudy Glavnoĭ Geofizicheskoĭ Observatorii (Transactions of the Central Geophysical Observatory), v. 1, no. 3, pp. 24-27, 1935a (in Russian).

MALKIN, N., On the application of Neumann's problem to the investigation of magnetic fields at altitudes lying above the regions of anomalies, loc. cit., pp. 28-43, 1935b (in Russian). (See abstracts of this and the preceding item in Geophysical Abstracts, v. 82, p. 1740, 1936.)

MORELLI, C., Anomalie magnetiche e declinazione in quota in Italia con speciale riguardo per la navigazione aerea strumentale, Geofis. Pura e Applic., v. 7, pp. 1-15, 1945 (in Italian).

PETERS, LEO J., The direct approach to magnetic interpretation and its practical application, Geophysics, v. 14, pp. 290-320, 1949.

SKEELS, D. C., and R. J. WATSON, Derivation of magnetic and gravitational quantities by surface integration, Geophysics, v. 14, pp. 133-150, 1949.

VESTINE, E. H., and Others, The geomagnetic field, its description and analysis, Carnegie Inst. Wash. Pub. 580, pp. 13-20, 1947.

Geophysics Section,
U. S. Geological Survey,
Washington 25, D. C.

(Communicated manuscript received March 7, 1951;
open for formal discussion until November 1, 1951.)

Transactions, American Geophysical Union Volume 32, Number 3 June 1951

MASS MOVEMENTS IN SUBMARINE CANYON HEADS

Francis P. Shepard

(Contribution from the Scripps Institution of Oceanography, New Series No. 519)

Abstract--The repetition of sounding profiles along precise ranges at the heads of the submarine canyons in the La Jolla area has given a sequence of depth changes during the past three years. Changes up to a maximum of 21 ft have been observed. Fill and deepening have alternated, but without any seasonal relationship such as occurs on the local beaches as a response to storm waves. The shallow valley heads are shown to shift in position, and at least one new valley with a maximum depth of 16 ft was formed during the period on an undissected slope. These changes have taken place on the sand-covered slopes inside the rock gorges and appear to be explained by sedimentation and landsliding. The latter may be a combination of creep and sudden shifting of sediment. Sufficient material is being moved by these slides to fill the outer gorges in a matter of a few centuries, but the material is certainly being carried out of the gorges, probably going to form the sand layers in the deep outer trough at the mouth of the canyon. The canyon heads are thought to trap a large proportion of the sand that is carried along the shore by currents. This prevents the formation of sand beaches directly down current from the canyons.

Introduction--The mass movement of sediments down the floors of submarine canyons is a phenomenon which is now well established. Cable companies have long been familiar with the slides at points where their cables cross canyons [SHEPARD, 1932], and engineers have had to contend with sudden deepenings at the ends of piers built into the heads of canyons, and with the slumping of jetties built at similar points. Detailed profiles across the shallow canyon heads off the California coast were first made in 1933. Many repetitions have been made since that time, and significant depth changes have been found on many occasions [SHEPARD and EMERY, 1941]. All the earlier work was carried on by wire soundings because echo-sounding devices were not available for the small boats which must be used for operations near shore and large boats are not practical for marine operations that require highly accurate positions. Since 1947 small portable echo-sounding devices have been available for the work at Scripps Institution, and these have been used on launches and amphibious vehicles (Dukws) for investigation of the changes in the canyon heads at La Jolla. The echo soundings are useful only in the shoalest portions of the canyons, largely because at greater depths the walls are so steep that the echoes become uncertain as to source and no consistency can be obtained in repeating runs. The results to date are by no means as complete as could be desired, so that the present is largely a report of progress.

The changing heads of Scripps Canyon

Accuracy of method--In order to find the exact nature of the changes which have taken place, it is of the utmost importance to have a high degree of accuracy in position and depth. There have been far too many reports of depth changes which are probably based on inaccurate positions, poor depth measurements, or faulty echo-sounding records. Some of our earlier records show definite evidence that changes have taken place, but the only thoroughly accurate and detailed information on canyon-head changes has come from the sounding records of the past three years in the two tributaries of Scripps Canyon known as Sumner Branch and South Branch (Fig. 1). Records of comparable accuracy at the head of La Jolla Canyon have shown much less significant changes. The axis slope of the small valleys at the canyon heads is approximately 6° out to 50 ft and 8° from 50 to 70 ft. Beyond, there are precipitous drops into rock-walled gorges. However, the echo-sounding surveys have adequately covered only the inner portions, where gently sloping, sand-covered walls are found.

A series of surveys has been made by echo sounding along 12 lines which cross the axes of the two canyon heads. These lines are rigidly controlled by very sharp ranges provided by the pilings of Scripps Institution pier, a half mile distant, and the peak of a white house a mile from the pier. Under small wave conditions it is easy to run a line keeping within one or two feet of these ranges. Positions along the range are obtained by marking positions on the tape when a series of pre-arranged sextant angles are observed. The accuracy of the method, at least as it

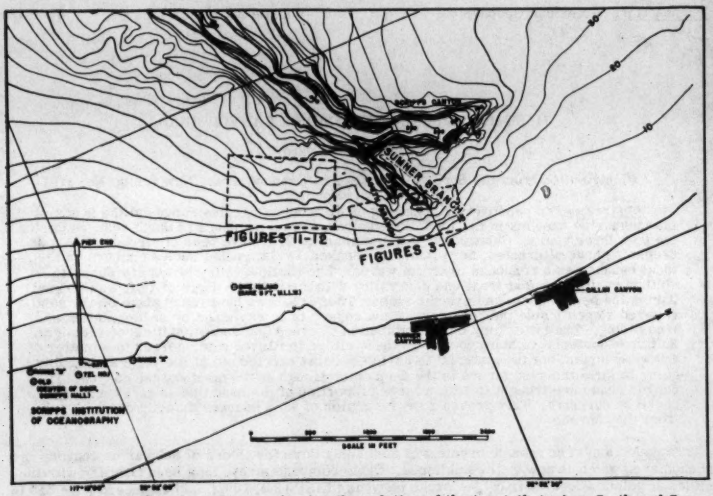


Fig. 1--The head of Scripps Canyon showing the relation of the two tributaries, South and Sumner Branches, to the main canyon; note the shallow valleys inside the rock gorges; changes in these inner valleys form the chief subject of discussion

applies to most of the ranges used in Figures 3 to 9, is indicated by Figure 2, in which two of the fathograms run as repeats on the same day or succeeding day are reproduced. The two outermost ranges are not as easily repeated because of the steep slopes. The records obtained from Scripps Canyon are corrected to the tide gage at the end of Scripps Institution pier so that there can be virtual certainty that no appreciable error comes from the state of the tide. The accuracy of the echo-sounding device is tested by comparing with vertical wire soundings at least twice during each survey. This is particularly important since variation of the frequency may cause errors which would imply depth changes of the order of a few per cent.

When complete checks are used, there can be no reasonable doubt of the existence of major changes such as we have discovered, particularly where they are indicated in a series of ranges.

Nature of changes--Three types of change are observed in the small valleys at canyon heads: one in which the axis depth increases or decreases, a second in which there is a change in the position of the valley axis, and a third in which new valleys develop. The second and third, so far as can be ascertained, are confined to zones where rock outcrops do not exist on the valley walls, but axis depth changes have been definitely established in localities where the canyon walls are rock cliffs.

The nature of the changes in Sumner and South Branches can be illustrated in various ways. Figure 3 gives a series of comparisons showing the progressive changes of contours in these valleys. These charts showed that the valleys under discussion have slight relief. Outward, they either die out or extend into the main branch. Intermediate Branch terminates offshore before extending into the gorge of Sumner Branch, whereas the gully at the head of South Branch is apparently related to the outer gorge. Even the latter is not very stable in position. The net change from January 1948 to February 1950 is shown in Figure 4. It will be noted that the valleys had nearly returned to their previous condition.

In the profiles taken directly from fathograms, comparison is made by superimposing one series on the next as in Figures 5 to 7. The vertical exaggeration in the echo-sounding profiles gives a false impression that actual new significant valleys are formed by some of the depth

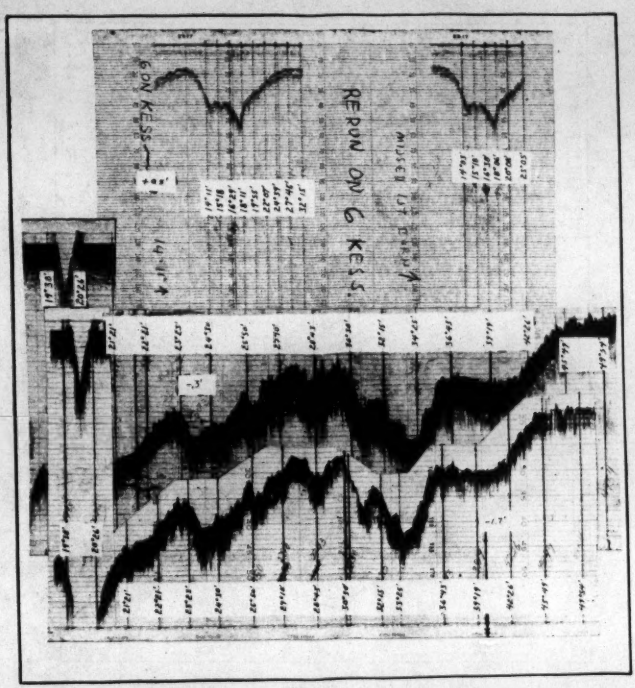


Fig. 2--Comparison of fathograms along the same ranges on the same day (upper) and on two successive days (lower); two different echo-sounding devices were used during the course of the work, accounting for the larger scale on the lower part of the figure; the spikes on the fathogram indicate waves; in judging depths, a line is drawn through these spikes; variations in speed of the boat prevent an exact tracing of one fathogram on top of the other, but the points of reference (given as angles) are for the most part exactly the same; note also that where the fathogram gets too deep for the scale (lower left), a shift can be made onto the next scale

changes. Examination of the accompanying contour maps, however, shows that the new valleys are very small in dimensions and some of them represent a redevelopment of pre-existing valleys.

Another and particularly significant means of comparison is shown in Figures 8 and 9, where the axis depths along each of the sections are plotted against time over the past three years. For South Branch these plottings were easily made since the valley axis could be traced outward continuously into the rock gorge beyond, although at times the inner depression became filled. However, Sumner Branch offered more of a problem since Intermediate Branch, the principal shallow inner gully, is not connected with the outer gorge. As a result, a different valley was used for the outer lines because it seemed advisable to show the changes in both of these features in order to compare the times of change in the different parts of the tributaries (Fig. 10). Examination of the profiles of axis change shows that there has been a series of deepenings occurring contemporaneously along most of the axis of the same branch and at slightly different times in the two branches.

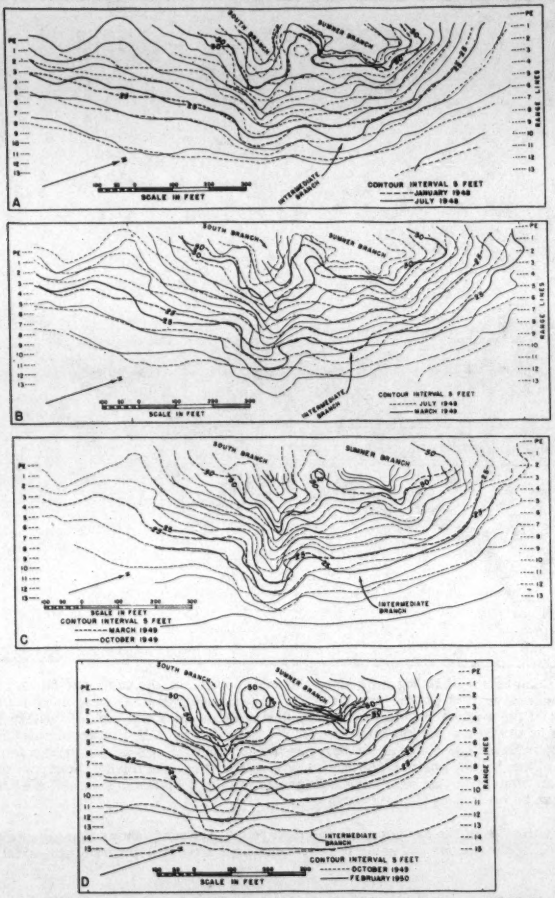


Fig. 3--Illustrating the changing contours in the shallow valleys at the heads of South and Sumner Branches; note that Intermediate Branch virtually disappears at times, also that at the time of the February 1950 survey South Branch had been filled in for a length of over 200 ft; as will be seen from Figure 8, the branch re-opened in May 1950; the accuracy of these large-scale maps becomes somewhat questionable along the outer lines

The cycles of fill and cut are variable in length in both canyons and certainly not related to the storm season. Both the cut and the fill were progressive during a sequence of surveys. It is

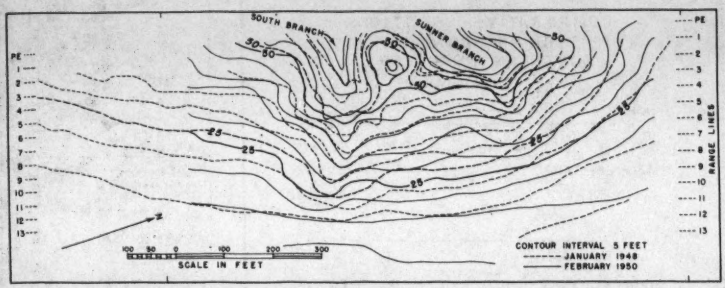


Fig. 4--Contour map showing the total change in contours in 25 months; note that in the February 1950 survey the valley heads have approximately the same depths as the valleys of the earlier survey, but that they are shifted in position

unfortunate that trouble with equipment made it impossible to determine whether or not the alternation of fill and cut which occurred between October 1949 and May 1950 was gradual or whether the changes took place rapidly. Future work with surveys more closely spaced in time is obviously needed.

New Valley development--The formation of a new valley formed somewhat to the south of South Branch deserves especial attention. One line had been run repeatedly across the area where the new valley appeared for almost three years before there was any indication of this valley (Fig. 7, 2 pile range). Subsequently New Valley (Fig. 11) has been completely surveyed and is found to have a maximum depth below the shelf of about 16 ft. The valley dies out in both directions and shows no indication of being connected directly with the rocky canyon outside. It has gentle slopes and is not an impressive feature. The time of valley development seems to have been after an earthquake which shook La Jolla enough to be widely felt, although no damage resulted. The changes in South and Sumner Branches observed after this earthquake were in the nature of fill (Fig. 3D and 7) which, however, may have been entirely independent of the earthquake.

Unfortunately only one line is available to show the changes between October 1949 and February 1950, but older lines are available which cover most of the length of the new valley. These show no sign of a pre-existing valley. It seems likely that the major changes which produced the entire valley took place at more or less the same time. The net changes on the sea floor are given in Figure 12, where contours are based on depth differences between the old and new lines. Examination of these contours or isopleths indicates that the changes represent the removal of material to a maximum depth of slightly over 20 ft along a portion of a slope which had an inclination of approximately four degrees.

Nature of bottom--The character of the bottom material in the changing valley heads inside the gorge is known as the result of considerable sampling as well as from observations during dives. As indicated previously, no rock has been found although the rock walls are closely adjacent to the outermost of the echo-sounding lines. The sediment is almost entirely fine sand but with a trace of silt. The median diameters shown from analyses indicate the sand varies from 0.160 to 0.108 mm, in general decreasing with depth. A maximum of about three per cent silt was found in the deeper samples (about 60 ft deep). The sand on adjacent portions of the shelf is comparable in grain size with the sand in the valleys. In the outer gorge, however, the sand is somewhat finer than on the adjacent shelf, and the silt content runs up as high as 60 per cent in some samples. In the shallow valleys, samples obtained after a fill had approximately the same diameters as those obtained after deepening.

In a considerable number of sampling attempts only eel grass or kelp was recovered. Some of this grass was so decomposed as to have a strong smell of H_2S. In places the sand was crossed by rows of echinoids (sand dollars). Ripple marks were found on the sand, with wave lengths of about three inches. In view of the depth, they are probably related to the surface wave action.

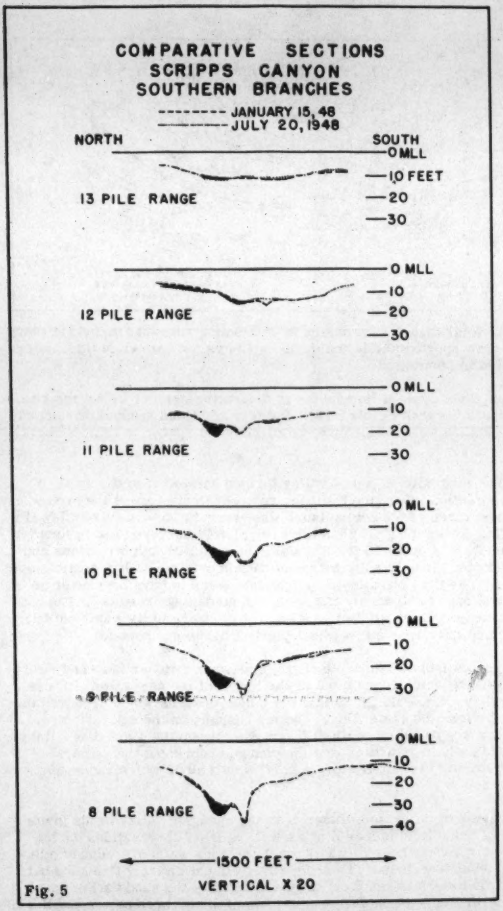


Fig. 5

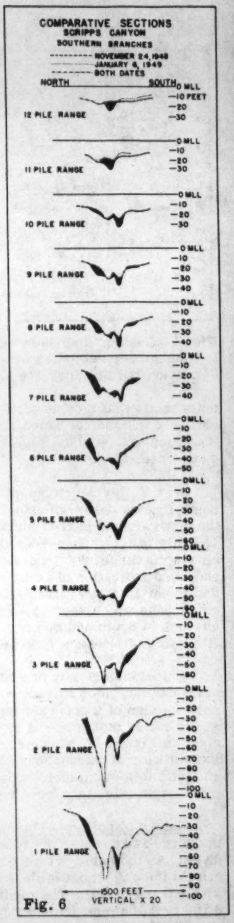


Fig. 6

Fig. 5--Superimposed tracings from fathograms (adjusted to give agreement as to position), illustrating the development of Intermediate Branch (left) between January 1948 and July 1948; the black area shows deepening; note that the right-hand valley (South Branch) was filled somewhat during this same period; it should be borne in mind that these sections show a great vertical exaggeration and comparison should be made with the contour maps to obtain a better idea of the actual slopes involved

Fig. 6--Superimposed tracings from fathograms of November 1948 and January 1949 (adjusted to give agreement as to position); the sections indicate the extension shoreward of the head of South Branch (right) and a considerable removal of material from the sides of Intermediate Branch (12 pile to 9 pile) and of Sumner Branch (8 pile to 5 pile)

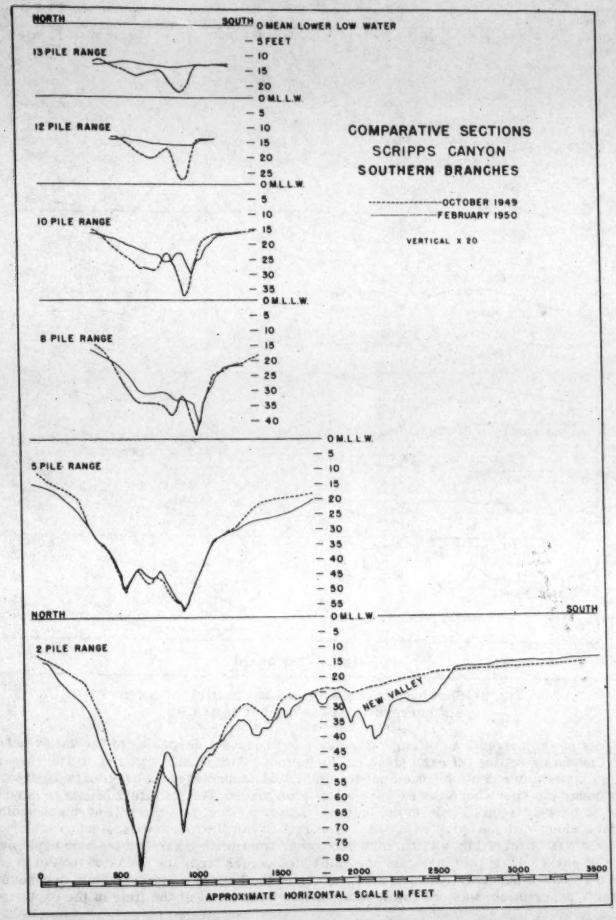


Fig. 7--Superimposed tracings from fathograms (adjusted to give agreement in position); these tracings are from fathograms of larger scale showing more details than those of Figures 5 and 6; note the development of New Valley between the times of these surveys, also the extensive fill in Intermediate and South Branches (see Fig. 3); the decreasing depth of the ridge shown between the two canyons along "2 pile range" is probably authentic although subject to slight uncertainty due to the steepness of the slopes. The authenticity of the development of New Valley is assured since numerous earlier surveys conformed with the October 1949 line and a series of surveys show absolute agreement with February 1950 (see Fig. 2)

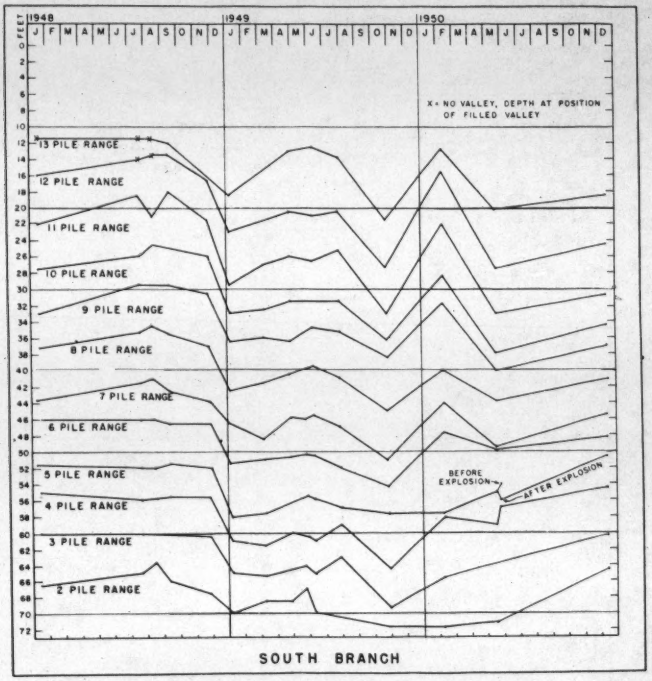


Fig. 8--Showing the sequence of cut and fill in three years of surveys along the head of one valley

Effects of explosives--An attempt was made to produce a deepening of the valley heads in Scripps Canyon by setting off explosives on the bottom. Although charges up to 100 lb were employed, no appreciable depth changes occurred. Local deepening of the order of two feet took place directly under the spot where the explosive had been placed, but the effect seems to have been only that of blowing a small hole in the bottom. Another effect was the boiling-up of sediment to the surface along with decaying eel grass. The rise of similar decomposed eel grass over the canyon axis was observed by a fisherman at another time when there had been no explosive or disturbance of any kind. In this last case the gas which comes from the decay of the eel grass must have been released suddenly, causing a boiling-up of the bottom material which, according to the fisherman's description, was not unlike that which we observed at the time of the explosions.

Amount of displaced sand--The comparative surveys show that in the course of a year a considerable amount of sand is displaced from the slopes inside the canyon heads. If this material moves out along the canyon axis, as seems likely, it would either cause a relatively rapid fill of the outer canyon or, if it is carried beyond, make an appreciable contribution of sand to the floor of San Diego Trough. Thus, for example, measurement by planimeter indicated a loss of 3,500,000 cu ft in the area shown in Figure 12, and nearly 4,000,000 cu ft in all was displaced in the formation of New Valley at the end of 1949, while in the change between February and May 1950 about 300,000 cu ft was moved. Assuming that the former change was exceptionally large, it is still not unlikely that a million cubic feet move out of the Scripps Canyon heads each year. If this is distributed evenly along the outer axis of Scripps Canyon, which extends for about one mile and has a

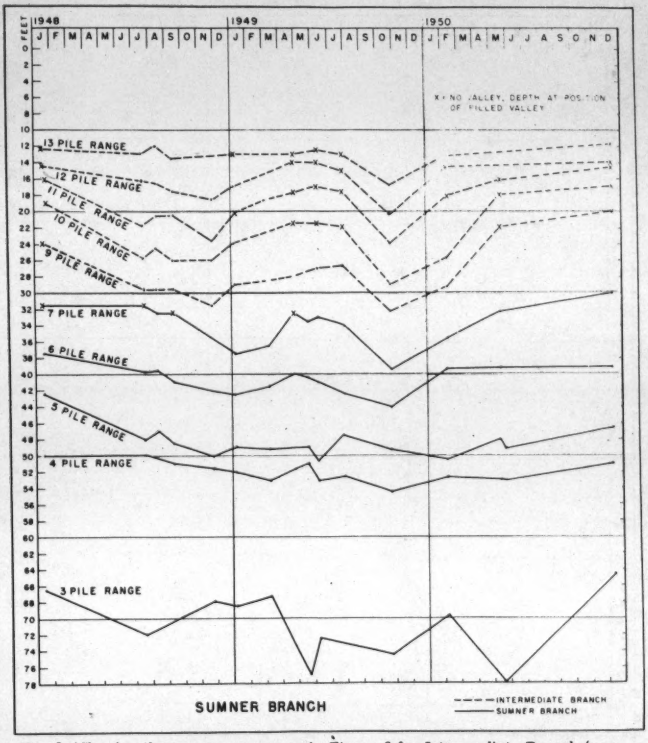


Fig. 9--Showing the same sequence as in Figure 8 for Intermediate Branch (profiles 13 to 9) and Sumner Branch (profiles 7 to 3); note the great increase in gradient indicated by the large interval between the 4th and 3rd pile

floor width of about 50 ft, it would cause an annual fill of the order of four feet. At this rate the canyon would be eliminated in a few centuries. It seems highly probable, however, that much of this displaced material continues beyond the main portion of Scripps Canyon. In fact, the sand layers found abundantly on the floor of San Diego Trough outside La Jolla Canyon [LUDWICK, 1950, and SHEPARD, 1951] can be most easily explained as having moved out of the canyon.

Nature of mass movements

The most obvious explanation for the deepenings in the valley heads is that there are occasional submarine landslides which carry material out into deeper water. Alternatives worth considering are (1) that large waves and their associated currents carry the material down the canyon axes [JOHNSON, 1939], and (2) that turbidity currents are set up by heavily-laden, muddy waters accompanying floods.

The available information suggests that landslides are the explanation and that the alternatives are at most of minor importance. Thus the times of deepening in the branches of Scripps

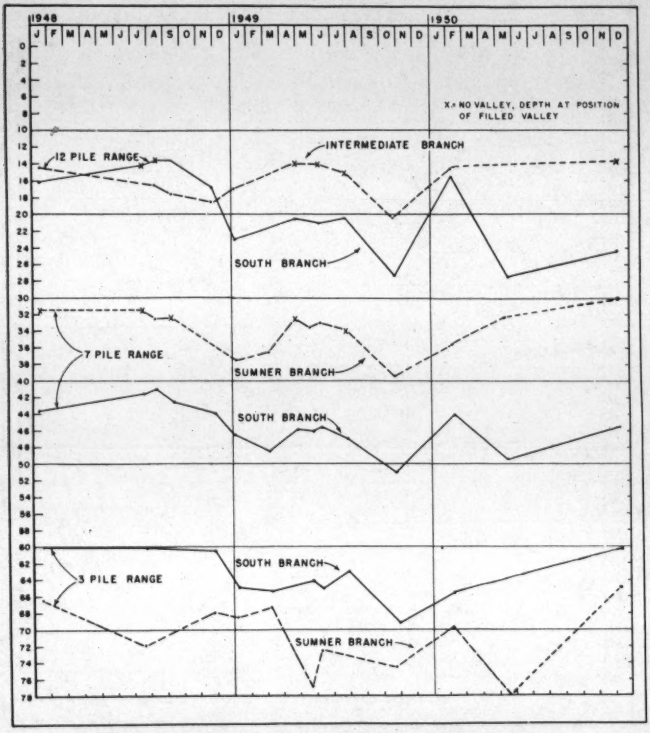

1948
1949
1950
J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D
X = NO VALLEY, DEPTH AT POSITION OF FILLED VALLEY
12 PILE RANGE
INTERMEDIATE BRANCH
SOUTH BRANCH
7 PILE RANGE
SUMNER BRANCH
SOUTH BRANCH
3 PILE RANGE
SOUTH BRANCH
SUMNER BRANCH

Fig. 10--A comparison of times of change in the heads of South Branch with those in Intermediate and Sumner Branches

Canyon include August to October 1949, a period when there were no unusually large waves nor were there any heavy rains which could have set up turbidity currents. Furthermore, the times of largest waves and most rain, that is, February through April, have been more the times of fill than deepening in the La Jolla Canyons. During the largest flood of recent years, March 1938, a sediment trap was in place on the floor of La Jolla Canyon. Recovery of the trap after the storm showed that no unusual movement had taken place and there was as much sediment on the down canyon as on the up canyon side.

The rapid deepenings of as much as 25 ft at the end of the Redondo City pier, built into the head of Redondo Canyon, are particularly indicative of submarine slides. According to fishermen on the pier, one of the deepenings took place in a period of one-half hour. It occurred at a time when there were relatively small waves and after a period of long-continued fill which had been recorded by the city engineer for a period of about a year. Other pier-end deepenings both at Redondo and at Moss Landing (at the head of Monterey Canyon) have occurred during storm-wave conditions, but the large scale and rapidity of deepening indicate that the storm waves were merely a trigger effect which set off a slide.

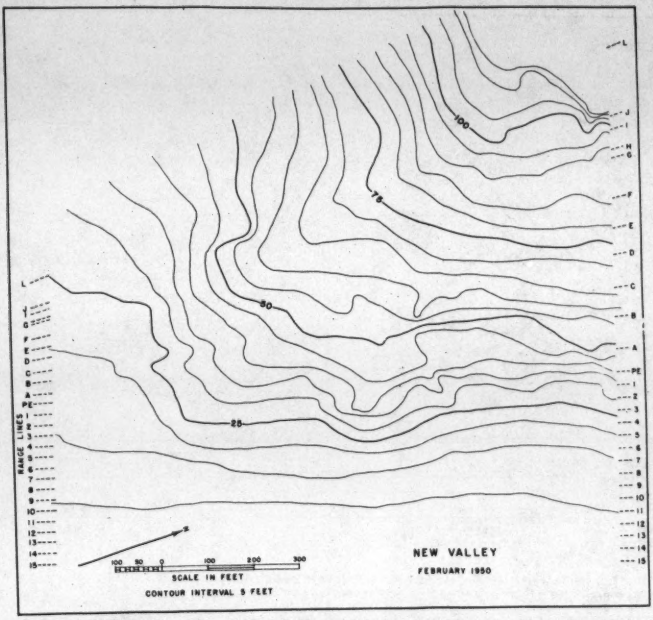


Fig. 11--Showing the shape of New Valley which developed between November 1949 and February 1950 (see also Fig. 12); note that it reaches a maximum in the middle and practically dies out outside as well as inside; it will be seen that this valley is very different from the great rock-walled gorges shown in Figure 1

Theoretically there are no serious difficulties in the assumption that slides of some nature produce the removal of the rapidly accumulating canyon head fill. Mass movements on land are known to occur at angles as low as one degree in mud and of about five degrees in sand (Karl Terzaghi, personal communication). Evidence of slides on the sea floor at angles as low as one degree has been reported [ARCHANGUELSKI, 1930]. Since there is some mud deposited along with the sand, the slopes at the canyon heads are sufficiently steep to induce slides even in saturated sediments on land so that they are presumably steep enough for movements on the sea floor where the displaced materials are more buoyant than on land. Furthermore, the inclusion of decaying kelp and eel grass in the sand results in the formation of pockets of gas which must greatly facilitate sliding action.

The evidence of successive deepenings suggests that slow slumping takes place in addition to the rather rapid slides indicated at pier ends. During a dive into Sumner Branch, Frank Haymaker discovered a trench a few inches deep and a few feet wide along the north side of the fill [SHEPARD, 1949, pl. 3, Fig. 2]. This feature may give some clue as to the types of movement which take place. However, until we are able to make daily observations or obtain continuous instrumental records in some of the deeper areas, considerable uncertainty is going to remain relative to the exact nature of these changes.

Significance of canyon head depth changes

The following questions arise as the result of the observed canyon head changes:

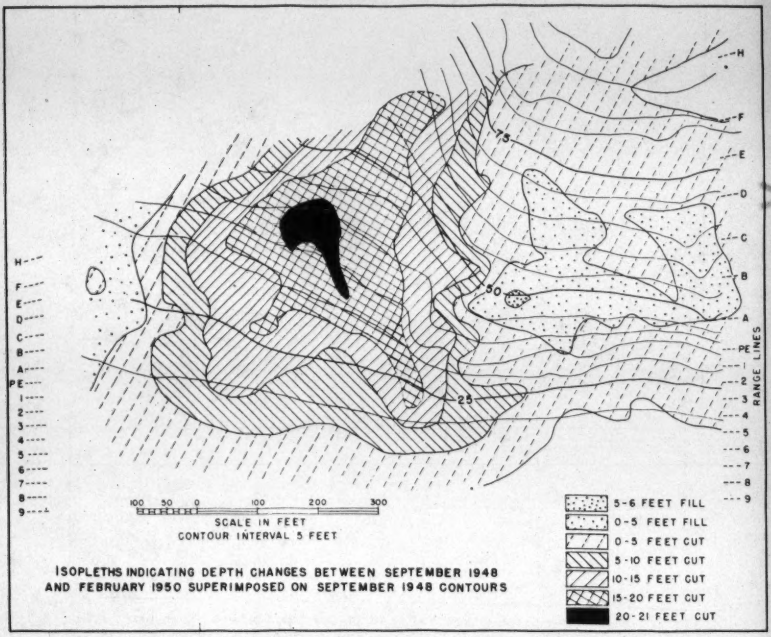


Fig. 12--Showing the magnitude of depth changes involved in the development of New Valley; note that part of the survey is based on soundings in 1948, but at least the major change quite certainly occurred after the October 1949 survey

(1) Does the greater portion of the sand being carried along the coast by longshore currents fall into the canyon heads and become permanently lost to the beaches?
(2) Are the canyon heads becoming slowly filled with sediment despite the occasional deepenings?
(3) Do slides occur with sufficient violence so that canyon floor erosion takes place with the result that the canyons are getting deeper?

Clear-cut answers to these questions are not yet possible, but clues which have come from the investigations may provide partial answers.

Canyon heads as sand traps--The period of three and a half months during which the head of South Branch was filled by as much as four to eight feet shows that a very considerable amount of sand (the type of sediment in the canyon head) must be carried into these valleys where they extend in near shore. This fill took place during a period when there was only a small amount of rain, so that the sediment must have been provided by the longshore transport of sediment by currents related to waves.

The currents associated with canyon heads [SHEPARD and INMAN, 1950] are not conducive to the by-passing of sediment. Commonly sediment is carried out from the shore by rip currents which extend out from the convergence zones on either side of the canyon heads. However, during times of longshore winds the longshore currents tend to flow past canyon heads with much less outward deflection. At La Jolla the coastal zones which are down current from the two canyon heads are virtually free of sand, which indicates that little sand passes the canyon heads. On the

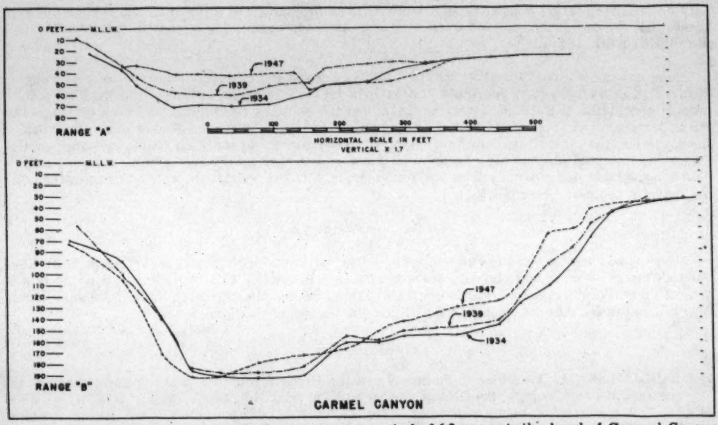


Fig. 13--Showing a series of depth changes over a period of 13 years in the head of Carmel Canyon; an important item of the change consists of a shift of the channels of the canyon head

other hand, the building of jetties at Hueneme, California, resulted in serious sand loss to the shore in a down-current direction, which seems to indicate that prior to the construction at least part of the littoral drift of sand was moving around Point Hueneme past the canyon head [INMAN, 1950]. The jetties apparently deflected this sand supply into the canyon so that it was no longer available for the down-current beaches.

It is possible that sediment dropped into submarine canyon heads can be returned to the beaches provided the slope is relatively gentle. The placing of a sediment trap in the very head of La Jolla Canyon above the zone of steep slope resulted in obtaining more sediment on the down canyon side than up canyon. However, this one case may not be very representative. It would certainly be surprising if sediment is moved up the five- to eight-degree slopes of the heads of Scripps Canyon and of course virtually impossible that sediment could move up the precipitous slopes which lead into the rock gorge. Material falling into these gorges must move down canyon since otherwise it would soon fill the canyons. As we have seen, even the inner slopes are ample for slides.

Net results of canyon head changes--The evidence regarding the ultimate fate of submarine canyons, provided conditions remain as at present, is by no means conclusive. The oldest soundings along good ranges across canyon axes date back to 1934. They are mostly in water deeper than that which has been discussed. Also, the interval may not be long enough to find any net change, but the changes may be considered for what they are worth. In Scripps Canyon a good range shows a depth of 483 ft in 1934 and 471 at the same place in 1948. In La Jolla Canyon, also on a good range, the depth in 1937 was 188 as compared with 184 in 1947. In Carmel Canyon (Fig. 13) the greatest depth in 1934 along a good range was 193 ft compared with 192 in 1947, while on another range it varied from 72 to 56 ft. All of these comparisons indicate a slight net shoaling, but the changes, some of which are scarcely outside the limits of operational errors, are no greater than the alternating changes at shoaler depths clearly demonstrated in the valleys at the head of Scripps Canyon. A change over a period of five years in Newport Canyon indicates slight deepening. Over longer periods we have the testimony of surveys dating back 60 years or more at certain canyon heads in California. However, because of paucity of soundings, all one can conclude from these older surveys is that there has probably been no appreciable landward extension of the canyon heads. Except where up-current breakwaters have trapped sand supplies, the beaches inside canyons show little change from the condition they had 50 years ago. Piers inside canyons are still located at the same place although some of them have undergone periodic slides as indicated previously.

Thus the evidence to date is that canyons are not undergoing any appreciable net changes. Sediment introduced at the heads eventually slides out along the axis. Whether the movement

outside the steep heads continues as a slide or is in the nature of a turbidity current is not yet known, but the movement of sand over very low slopes is suggestive of turbidity current transport [SHEPARD, 1951].

The cores obtained along the axis of La Jolla Canyon indicate that material may be very slowly filling the canyon, since there are various layers of coarse sediment interbedded with muddy materials. If the slides were scouring out the canyons completely and even cutting away the underlying rock, one would expect to find only thin layers of fine sediment overlying rock floors rather than the alternating layers shown in the cores. In the East Coast canyons, cores suggest that deposition has been going on at least as far back as the last glacial stages--since cold water planktonic Foraminifera are found underlying the temperate water Foraminifera of the upper sediments [PHLEGER, 1942].

Acknowledgments

Very able assistance in various phases of this work has been given the writer by Ruth Young, Douglas Inman, Don Sayner, David Poole, and George Brayton. The drafting was done by Don Sayner. This work represents in part research carried out for the Office of Naval Research and the Beach Erosion Board under contracts with the University of California.

References

ARCHANGUELSKI, A. D., Slides of sediments on the Black Sea bottom and the importance of the phenomenon for geology, Soc. Naturalistes Moscou Bull. Sci. Geol., N. S., v. 38, p. 80, 1930.

INMAN, D. L., Report on beach study in the vicinity of Mugu Lagoon, California, Beach Erosion Board Tech. Memo. no. 14, 47 pp., 1950.

LUDWICK, J. C., JR., Deep water sand layers off San Diego, California, doctoral thesis, Scripps Inst. Oceanog., 1950.

JOHNSON, D. W., Origin of submarine canyons, New York, 126 pp., 1939.

PHLEGER, F. B., Foraminifera of submarine cores from the continental slope, pt. 2, Bull. Geol. Soc. Amer., v. 53, p. 1077 and pl. 3, 1942.

SHEPARD, F. P., Landslide-modifications of submarine valleys, Trans. Amer. Geophys. Union, v. 13, pp. 226-230, 1932.

SHEPARD, F. P., Terrestrial topography of submarine canyons revealed by diving, Bull. Geol. Soc. Amer., v. 60, pp. 1597-1612, 1949.

SHEPARD, F. P., Sand and gravel in deep-water deposits, World Oil, v. 132, pp. 61-68, 1951.

SHEPARD, F. P., and K. O. EMERY, Submarine topography off the California coast, Geol. Soc. Amer. Spec. Paper no. 31, pp. 94-102, 1941.

SHEPARD, F. P., and D. L. INMAN, Nearshore water circulation related to bottom topography and wave refraction, Trans. Amer. Geophys. Union, v. 31, pp. 196-212, 1950.

Scripps Institution of Oceanography,
La Jolla, California

(Communicated paper received December 29, 1950;
open for formal discussion until November 1, 1951.)

Transactions, American Geophysical Union Volume 32, Number 3 June 1951

A MIXING-LENGTH THEORY OF TIDAL FLUSHING

Arnold B. Arons and Henry Stommel

(Contribution No. 544 of the Woods Hole Oceanographic Institution
under contract with the Office of Naval Research)

Abstract--The salinity distribution in an idealized estuary where mixing is predominantly due to the tides is computed, using an eddy diffusivity based on the distribution of tidal currents and excursions. Comparison is made to the salinity distribution in real estuaries.

Introduction--The method of computing the steady-state salinity distribution in an estuary due to KETCHUM [in press] is essentially a refinement of the older tidal prism concept used by engineers for many years. The estuary is subdivided along its axis into a number of volumes, each of which is as long as the average excursion of the tide. Complete mixing takes place within each volume. Ketchum has obtained remarkably good agreement between observed salinity distributions along the axis of the Raritan estuary. This success prompted us to attempt a translation of Ketchum's fundamental idea - that the element of mixing volume is bounded by the length of the tidal excursion - into the language of physics of continua.

Kinematics of the model--Consider an estuary of uniform width w, depth H, length L. The origin is placed at the river inflow where the salinity is maintained at $s = 0$. The x-axis is directed positively downstream. At the seaward end of the estuary, $x = L$, the salinity is maintained at that of the open ocean $s = \sigma$.

The river discharge is D (cu ft/min). The mean velocity of water in the channel due to the river is therefore $a = D/wH$.

If the length of the channel is small compared to a quarter tidal wave length, the tide will be simultaneous and uniform over the entire channel, and we may express the height of the tide as $\xi = \xi_0 \cos \omega t$, where ω is the angular frequency of the tide.

The tidal current U is obtained from the equation of continuity.

$$\partial \xi / \partial t = - H \partial u / \partial x \quad \ldots\ldots (1)$$

$$U = U_0 \sin \omega t \quad \ldots\ldots (2)$$

where

$$U_0 = \xi_0 \omega x / H \quad \ldots\ldots (3)$$

The average tidal displacement, ξ, is obtained by integration of the tidal velocity

$$\xi = \xi_0 \cos \omega t \quad \ldots\ldots (4)$$

where

$$\xi_0 = - \xi_0 x / H \quad \ldots\ldots (5)$$

The salt-transfer equation--We will consider the equation describing the mean salinity distribution

$$\partial s / \partial t + u \partial s / \partial x = \partial (A \partial s / \partial x) / \partial x \quad \ldots\ldots (6)$$

In this equation s is the time mean salinity at any point x, u is the time mean velocity at x, which we may take as that portion of the flow due to the river (that is, $u = a$), and A is eddy diffusivity along the x-axis. We express A in terms of a dimensionless number B, a characteristic

velocity which we take as the tidal amplitude U_0, and a characteristic length which we take as $2\xi_0$, the total excursion of a particle due to the tides.

$$A = 2B\,\xi_0\,U_0 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (7)$$

This form of diffusion equation regards the tides as a turbulent motion superposed upon the steady river flow through the estuary. The simple assumed form of the eddy-diffusivity coefficient is the equivalent of Ketchum's assumption of the dimensions of the mixing volume. It should be clear to the reader that the simplicity of both of these formulations results from a certain vagueness about the physical process involved; the effects of stratification, stability, vertical mixing, bottom roughness, and other influences are not investigated.

In the steady state the time derivative vanishes, and (6) is integrable

$$a\,s = A\,ds/dx + C \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (8)$$

where C is a constant of integration. At $x = 0$, both $s = 0$ and $A\,ds/dx \neq 0$, because there can be no transfer of salt up the river by eddy diffusion; thus the constant of integration $C = 0$.

The form of the coefficient of eddy diffusion--From (3), (5), and (7) we see that A may be expressed as a function of x

$$A = 2B\,\xi_0^{\,2}\,\omega\,x^2/H^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (9)$$

Integration of the salt transfer equation--It is convenient to introduce a dimensionless parameter

$$\lambda = x/L \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (10)$$

to express the distance along the channel in fractions of the total length, and a dimensionless parameter

$$F = a\,H^2/2B\,\xi_0^{\,2}\,\omega L \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (11)$$

which we may call the "flushing number."

Making these various substitutions in (8) the following equation is obtained

$$Fs = \lambda^2\,ds/d\lambda$$

Integration by separation of variable yields the following expression

$$\log_e s = F/\lambda + C'$$

At $\lambda = 1$, $s = \sigma$, so that the constant of integration C is given by

$$C' = F + \log_e \sigma$$

Therefore, it is possible to write the ratio of mean salinity to the ocean salinity in exponential form

$$s/\sigma = e^{F(1-1/\lambda)}$$

The salinity distribution function s/σ --The family of curves on the relation of λ to s/σ is shown in Figure 1 for various values of the flushing number F.

Empirical data for both Alberni Inlet, Vancouver Island, and the Raritan River, New Jersey, are plotted on this figure.

The family of curves is interesting for several reasons: (1) There is a toe to the curves near $\lambda = 0$. (2) The curves are very sensitive to F in region $0.1 < F < 10$. (3) There is a point of inflection at $\lambda = F/2$.

Convenient alternative forms of the flushing number are

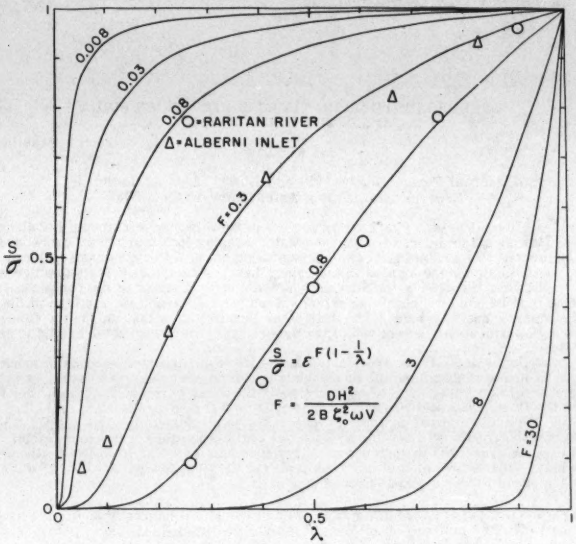


Fig. 1--Family of curves showing relation of λ to s/σ

$$F = D H^2/2B \xi_0^2 \omega V = D H^2 T/4\pi B \xi_0^2 V = R H^2/4\pi B \xi_0^2$$

where D is the river discharge, T is the tidal period, V is the mean total estuary volume, and R is the river discharge per tidal cycle.

Interpretation--The curves presented here were developed for a very much idealized situation. For that reason it is somewhat surprising and encouraging to find that empirical data from actual surveys can be plotted on the family with such good agreement.

An attempt to calculate the proportionality factor B from the data was unsuccessful, the values being of an order of magnitude different for the two cases. Therefore, it appears that although the shape of the theoretical curves is in good agreement with the observations at hand, an a priori calculation of the flushing number is not yet feasible. Nevertheless, the flushing number may be a convenient concept to characterize estuaries, just as the family of curves themselves is a convenient semi-empirical expression of the mean salinity distribution.

References

KETCHUM, B. H., The exchanges of fresh and salt waters in tidal estuaries, J. Mar. Res., in press.

TULLY, JOHN P., Oceanography and prediction of pulp mill pollution in Alberni Inlet, Fish. Res. Bd., Canada, Bull. 83, 169 pp., 1949.

Woods Hole Oceanographic Institution,
Woods Hole, Massachusetts

(Communicated manuscript received November 24, 1950;
open for formal discussion until November 1, 1951.)

Transactions, American Geophysical Union Volume 32, Number 3 June 1951

SEEPAGE INTO DRAIN TUBES IN STRATIFIED SOIL
I - DRAINS IN THE SURFACE STRATUM

Don Kirkham

(Journal Papers Nos. J-1824 and J-1827, Iowa Agricultural Experimental Station, Ames, Iowa, Project 998)

Abstract (both Parts)--Expressions for the drain flow, the surface inflow distribution, and flow nets are derived for surface water seeping into drain tubes embedded in water-saturated soil consisting of two horizontal strata of different permeabilities. In Part I, the drain tubes are located in the upper layer. Numerical results are presented. It is shown in the case of the flow nets how Kennelly's tables of the complex hyperbolic sine may be used to obtain numerical values for equipotentials and stream lines simultaneously. The flow nets, as well as other results, show that unless the lower layer is of high permeability compared to the upper layer, the lower layer has little effect on the flow.

In Part II, the drain tubes are located in the lower layer which extends to great depth. It is shown that, unless the drain tubes are very near the upper layer, or unless the upper and lower layers are of approximately the same permeability, the lower layer governs the flow. Quantitative results are worked out for several cases, including a flow net. The mathematical analysis in both cases is presented in some detail. This is done so that the reader will be able to work out certain details readily for himself. But the material is presented in such a way that readers not desiring to follow mathematical details may, without loss of continuity, skip all but the first few paragraphs of the Analysis and proceed to Results and Discussion.

In several earlier papers the author has obtained analytical expressions for the seepage rate into drain tubes of water in a soil of uniform permeability [KIRKHAM, 1945, 1949]. A more common case, however, is that where the soil consists of an upper layer of one permeability underlain by another layer of another permeability, the lower layer being commonly of the lower permeability. In draining excess water from such stratified soil, the drains may be located in either the upper or lower layer. Part I of this paper analyzes the case when the drains are in the upper layer. Part II considers the case when the drains are in the lower layer. The analysis, because of the nature of the problem, is rather long, but the results are obtained in terms of well-known functions, and lend themselves to relatively easy calculation. Readers not desiring to follow the mathematical details of the problem may skip the Analysis, except for the first one or two paragraphs describing Figure 1, which represents the geometry of the problem, and pass to Results and Discussion of Results.

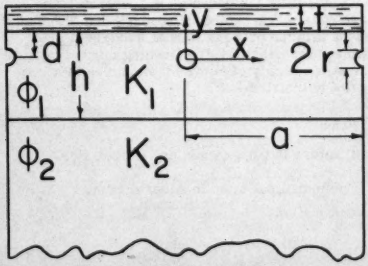


Fig. 1--Vertical section of field with ponded water and drain tubes; section is taken perpendicular to the drain tubes which are assumed to be equally spaced and horizontal

Analysis

In Figure 1 homogeneous soil in two horizontal stratified layers of different permeabilities, K_1 in the upper layer, and K_2 in the lower, is represented. The soil is saturated with water to the surface and there covered with ponded water to thickness t. The upper layer of soil is of thickness h; the lower layer is of effectively infinite thickness. Circular drain tubes of radius r are embedded in the soil at equal spacing a and depth d. The drain tubes are assumed to be completely permeable over their whole length, and it is assumed that no water leaves the soil except through the drain tubes. The drains and soil are taken to extend uniformly a great distance in the horizontal direction. Therefore, the problem is one of two dimensions. The origin of coordinates is taken at the center of a drain, the y-axis vertically upward, and the x-axis horizontally to the right.

Darcy's law is assumed valid in both regions so that the problem is one of potential theory. The appropriate potentials in the upper and lower layers are designated by ϕ_1 and ϕ_2. For purposes of analysis, a region of permeability K_0 is first taken to extend to infinity above the soil surface, the potential for this region being denoted by ϕ_0. The procedure here is similar to that used by HUMMEL [1929] in the problem of the flow of electricity in stratified layers of soil. The potential ϕ_0 is first evaluated for an unrestricted value of K_0, but in the final result K_0 is set equal to infinity to take account of the infinite permeability of the ponded water. That the ponded water does not extend upward to infinity, but only to thickness t, is provided for when the boundary conditions are evaluated. In Hummel's problem the quantity corresponding to the present K_0 is set equal to zero. Also, he considers point sources and sinks of electricity; whereas here line sources and sinks of water are in question.

Derivation of the potential functions--Taking the potential functions ϕ_1 and ϕ_2 for each region in the form (for conventions with regard to the use of the solidus, see KIRKHAM [1949], pp. 369-370).

$$\phi = (p/\gamma g + y)$$

where p is the gage hydrostatic pressure at a point in the soil, y the coordinate of this point, γ the density of the water in the soil, and g the acceleration of gravity. Physically, ϕ is the height referred to a horizontal plane through the origin of coordinates to which water would stand in a piezometer, the end of which is located at the point in question; ϕ is, therefore, the hydraulic head referred to a horizontal plane passing through the drain centers.

Differential equations and boundary conditions to be satisfied are

$$\left.\begin{aligned} &\nabla^2\phi_0 = 0, \text{ in region zero; } \nabla^2\phi_1 = 0, \text{ in region 1} \\ &\nabla^2\phi_2 = 0, \text{ in region 2} \end{aligned}\right\} \quad \text{Condition (I)}$$

At the 0-1 interface

$$y = d \qquad \phi_0 = \phi_1 \qquad \text{Condition (IIa)}$$

$$y = d \qquad K_0\partial\phi_0/\partial y = K_1\partial\phi_1/\partial y \qquad \text{Condition (IIb)}$$

At the 1-2 interface

$$y = -(h - d) \qquad \phi_1 = \phi_2 \qquad \text{Condition (IIIa)}$$

$$y = -(h - d) \qquad K_1\partial\phi_1/\partial y = K_2\partial\phi_2/\partial y \qquad \text{Condition (IIIb)}$$

At the surface of the soil next to the ponded water (a special case of Condition (IIa) when $K_0 = \infty$)

$$y = d \qquad \phi_1 = t + d \qquad \text{Condition (IV)}$$

At the surface of the drain, for example, at the top of the drain (assumed running full)

$$y = r, x = 0 \qquad \phi_1 = r \qquad \text{Condition (V)}$$

At great depth

$$y \to -\infty \qquad \partial\phi_2/\partial y \to 0 \qquad \text{Condition (VI)}$$

On vertical plans passing through drain centers, but excluding those parts of the planes inside the drains

$$x = 0, a, -a, \ldots, |y| \geq r \qquad \partial\phi_0/\partial x = \partial\phi_1/\partial x = \partial\phi_2/\partial x = 0 \qquad \text{Condition (VII)}$$

Condition (VI) demands, physically, that no water leave the soil at great depths. Water may leave only via the drain tubes. Condition (VII) demands that the solution be periodic in the x-direction. The hydraulic head will be finite at $y = -\infty$.

In order to satisfy the boundary conditions the method of images appears feasible. Use of Bessel functions as applied to Hummel's problem by STEFANESCO and SCHLUMBERGER [1930] does not appear feasible, since, here, as noted above, line sources and sinks are dealt with rather than point sources and sinks as in Hummel's problem.

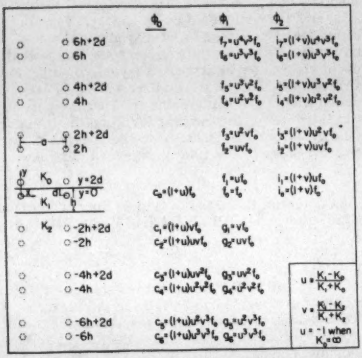


Fig. 2--Image array and flow coefficients corresponding to Figure 1; in final results K_0, which does not appear in Figure 1, is set equal to infinity and vanishes from the analysis

In using the method of images, it appears, on the basis of a simpler potential problem [JEANS, 1933, p. 200], that three sets of images will be needed, one set for each potential function.

The set of images for ϕ_1 must be located as in two earlier problems [KIRKHAM, 1945, 1949], because the present problem comprises the earlier problems as special cases. The present problem corresponds to the 1945 problem if $K_0 = K_2 = \infty$, and to the 1949 problem if $K_0 = \infty$ and $K_2 = 0$. Thus, the images for ϕ_1 must be located at $y = \pm 2nh + 2d$ and at $y = \pm 2nh$, where n takes all integral values, positive and negative, including zero. The location of these images and of the actual drains is indicated in Figure 2.

The location of the image arrays for ϕ_0 and ϕ_2 depends on the following reasoning. Since there can be no sources or sinks in region 0 or in region 2, no image in the array for ϕ_0 may lie above y = d and no image in the array for ϕ_2 may lie below y = - (h - d). Therefore, the array for ϕ_0 can be located only at $y = - 2nh + 2d$ (n = 1, 2, 3, ...) and at $y = - 2nh$ (n = 0, 1, 2, 3, ...); and for ϕ_2 at $y = 2nh + 2d$ (n = 0, 1, 2, 3, ...) and $y = 2nh$ (n = 0, 1, 2, 3, ...).

The present image systems differ from the systems in the earlier problems in that, whereas formerly the same flow coefficient $\pm q$ was associated with each row of drains and image drains, there must now be associated a different flow coefficient with each row. These coefficients (Fig. 2) are denoted by c's, f's, g's, and i's -- the c's for ϕ_0; the f's and g's for ϕ_1, and the i's for ϕ_2. The coefficients together with their values, immediately to be derived, are presented in Figure 2. The figure has been prepared to show at a glance the row with which each coefficient is associated. Figure 2 has proved to be indispensable in the analysis.

Evaluation of the flow coefficients--The potential ϕ' to be associated with each row of drains is of the form [KIRKHAM, 1945]

$$\phi' = q \log_e \cosh 2\pi y'/a - \cos 2\pi x'/a \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where y' and x' are coordinates of a point referred to an origin taken at the center of one of the drains, image or real. With the aid of (1) and Figure 2, and using the abbreviation

$$X = \cos 2\pi x/a \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

expressions for ϕ_0, ϕ_1, and ϕ_2 may now be written down to within additive constants as follows

$$\phi_0 = c_0 \log_e (\cosh 2\pi y/a - X) + c_1 \log_e [\cosh 2\pi (y + 2h - 2d)/a - X]$$
$$+ c_2 \log_e [\cosh 2\pi (y + 2h)/a - X] + c_3 \log_e [\cosh 2\pi (y + 4h - 2d)/a - X]$$
$$+ \ldots \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

$$\phi_1 = f_0 \log_e (\cosh 2\pi y/a - X) + f_1 \log_e [\cosh 2\pi (y - 2d)/a - X]$$
$$+ f_2 \log_e [\cosh 2\pi (y - 2h)/a - X] + f_3 \log_e [\cosh 2\pi (y - 2h - 2d)/a - X]$$
$$+ \ldots$$
$$+ g_1 \log_e [\cosh 2\pi (y + 2h - 2d)/a - X] + g_2 \log_e [2\pi (y + 2h)/a - X]$$
$$+ g_3 \log_e [\cosh 2\pi (y + 4h - 2d)/a - X] + \ldots \quad \ldots\ldots\ldots\ldots\ldots\ldots (4)$$

$$\phi_2 = i_0 \log_e (\cosh 2\pi y/a - X + i_1 \log_e [\cosh 2\pi (y - 2d)/a - X]$$

$$+ i_2 \log_e [\cosh 2\pi (y - 2h)/a - X] + i_3 \log_e [\cosh 2\pi (y - 2h - 2d)/a - X]$$

$$+ \ldots \quad \ldots\ldots\ldots\

$$I_0 = i_0 \log_e (\cosh 2\pi y/a - X) = (1 + v) f_0 \log_e (\cosh 2\pi y/a - X)$$

$$I_1 = i_1 \log_e [\cosh 2\pi (y - 2d)/a - X] = -(1 + v) f_0 \log_e [\cosh 2\pi (y - 2d)/a - X]$$

$$I_2 = i_2 \log_e [\cosh 2\pi (y - 2h)/a - X] = -(1 + v) vf_0 \log_e [\cosh 2\pi (y - 2h)/a - X]$$

Then one finds at the 1-2 interface where $y = -h + d$ that $F_0 + G_1 = I_0$, $F_1 + G_2 = I_1$, $F_2 + G_3 = I_2$, etc.; also, since $(K_1/K_2) = (1 + v)/(1 - v)$, that $K_1(\partial/\partial y)(F_0 + G_1) = K_2(\partial/\partial y)I_0$, $K_1(\partial/\partial y)(F_1 + G_2) = K_2(\partial/\partial y)I_1$, $K_1(\partial/\partial y)(F_2 + G_3) = K_2(\partial/\partial y)I_2$, etc. Thus, introducing a superscript notation, the boundary conditions at the 1-2 interface are satisfied by the successive pairs of values, reading from left to right.

$$\phi_1^{(1)} = F_0 + G_1 \qquad \phi_2^{(1)} = I_0$$

$$\phi_1^{(2)} = F_0 + F_1 + G_1 + G_2 \qquad \phi_2^{(2)} = I_0 + I_1$$

$$\phi_1^{(3)} = F_0 + F_1 + F_2 + G_1 + G_2 + G_3 \qquad \phi_2^{(3)} = I_0 + I_1 + I_2$$

$$\phi_1^{(4)} = F_0 + F_1 + F_2 + F_3 + G_1 + G_2 + G_3 + G_4 \qquad \phi_2^{(4)} = I_0 + I_1 + I_2 + I_3$$

....

Now the above values of $\phi_1^{(n)}$, although they satisfy Conditions (IIIa) and (IIIb), will in general not satisfy Condition (IV). But if a $\phi_1^{(n)}$ is chosen so that it terminates in G_2 or G_4 or G_6, etc. (with the corresponding $\phi_2^{(n)}$ terminating in I_1, I_3, I_5, etc.), all terms except the last two in this $\phi_1^{(n)}$ will add up identically to zero at $y = d$; and, if a $\phi_1^{(n)}$ with a sufficient number of terms is taken (the number depending on the values of h, d, and a) the last two terms in this $\phi_1^{(n)}$ will approach a constant value and boundary Conditions (IV) and (III) can be satisfied simultaneously. With these points in mind the following sets of expressions are obtained.

If
$$2h - d > a \quad \ldots\ldots (12a)$$

$$\phi_1^{(1)} = F_0 + F_1 + G_1 + G_2 + (4\pi d/a)vf_0 + t + d \quad \ldots\ldots (12b)$$

$$\phi_2^{(1)} = I_0 + I_1 + (4\pi d/a)vf_0 + t + d \quad \ldots\ldots (12c)$$

If
$$4h - d > a \quad \ldots\ldots (13a)$$

$$\phi_1^{(2)} = (F_0 + F_1) + (G_1 + G_2) + (F_2 + F_3) + (G_3 + G_4) - (4\pi df_0/a)v^2 + t + d \quad \ldots\ldots (13b)$$

$$\phi_2^{(2)} = (I_0 + I_1) + (I_2 + I_3) - (4\pi d/a)v^2 f_0 + t + d \quad \ldots\ldots (13c)$$

If
$$6h - d > a \quad \ldots\ldots (14a)$$

$$\phi_1^{(3)} = (F_0 + F_1) + (G_1 + G_2) + (F_2 + F_3) + (G_3 + G_4) + (F_4 + F_5) + (G_5 + G_6) + v^3(4\pi d/a)f_0 + t + d \quad \ldots\ldots (14b)$$

$$\phi_2^{(3)} = (I_0 + I_1) + (I_2 + I_3) + (I_4 + I_5) + v^3(4\pi d/a)f_0 + t + d \quad \ldots\ldots (14c)$$

In general, if

$$2nh - d > a \qquad n = 1, 2, 3, \ldots \quad \ldots\ldots (15a)$$

$$\phi_1 = f_0 \Bigg\{ \log_e \frac{\cosh 2\pi y/a - X}{\cosh 2\pi (y - 2d)/a - X} + v \log_e \frac{\cosh 2\pi (y + 2h - 2d)/a - X}{\cosh 2\pi (y + 2h)/a - X}$$

$$- v \log_e \frac{\cosh 2\pi (y - 2h)/a - X}{\cosh 2\pi (y - 2h - 2d)/a - X} - v^2 \log_e \frac{\cosh 2\pi (y + 4h - 2d)/a - X}{\cosh 2\pi (y + 4h)/a - X}$$

$$+ v^2 \log_e \frac{\cosh 2\pi (y - 4h)/a - X}{\cosh 2\pi (y - 4h - 2d)/a - X} + v^3 \log_e \frac{\cosh 2\pi (y + 6h - 2d)/a - X}{\cosh 2\pi (y + 6h)/a - X}$$

$$- \ldots \qquad - \ldots$$

(Equation continued on next page)

$$- (-1)^n v^{n-1} \log_e \frac{\cosh 2\pi [y - (2n - 2)h]/a - X}{\cosh 2\pi [y - (2n - 2)h - 2d]/a - X}$$

$$- (-1)^n v^n \log_e \frac{\cosh 2\pi (y + 2nh - 2d)/a - X}{\cosh 2\pi (y + 2nh)/a - X} \Big\} - (-1)^n v^n (4\pi d/a) f_o + t + d \quad \ldots\ldots (15b)$$

$$\phi_2 = (1 + v) f_o \Big(\log_e (\cosh 2\pi y/a - X)/[\cosh 2\pi (y - 2d)/a - X]$$

$$- v \log_e [\cosh 2\pi (y - 2h)/a - X]/[\cosh 2\pi (y - 2h - 2d/a - X]$$

$$+ v^2 \log_e [\cosh 2\pi (y - 4h)/a - X]/[\cosh 2\pi (y - 4h - 2d)/a - X]$$

$$- \ldots$$

$$- (-1)^n v^{n-1} \log_e \Big\{ \cosh 2\pi [y - (2n - 2)h]/a - X \Big\} / \Big\{ \cosh 2\pi [y - (2n - 2)h - 2d]/$$

$$a - X \Big\} \Big) - (-1)^n v^n (4\pi d/a) f_o + t + d \quad \ldots\ldots (15c)$$

Equations (15b) and (15c) remain to be checked against Conditions (VI) and (VII). Condition (VI) is satisfied because at $y \to -\infty$ the coefficients of $v^0, v^1, v^2, \ldots$, each approach the constant value $\pm 4\pi d/a$. Condition (VII) is also easily seen to be satisfied.

In (15b) and (15c) any desired degree of accuracy is obtained by taking n sufficiently large. When n is sufficiently large, f_o times the last term in the braces in (15b) cancels the term $-(-1)^n v^n (4\pi d/a) f_o$ for all values of y. This observation is tacitly used in obtaining equation (17) below, where y of (15b) equals r.

Computation of f_o--The constant f_o is obtained by applying condition V to (15b). The result is

$$f_o = (t + d - r)/A \quad \ldots\ldots (16)$$

where A is the negative value of the expression in the braces in [15b] with y set equal to r and x set equal to zero.

Taking then $y = r$ and $x = 0$ so that $X = 1$, and noting that $\cosh(-B) = \cosh B$ and that $\cosh B - 1 = 2 \sinh^2 B/2 - 1$, A of (16) may be obtained in the form

$$A = 2 \Big(\log_e [\sinh \pi (2d - r)/a]/\sinh \pi r/a$$

$$+ v \log_e \Big\{ [\sinh \pi (r + 2h)/a]/\sinh \pi (r + 2h - 2d)/a \Big\} \Big\{ [\sinh \pi (2h - r)/a]/\sinh \pi (2h + 2d - r)/a \Big\}$$

$$- v^2 \log_e \Big\{ [\sinh \pi (r + 4h)/a]/\sinh \pi (r + 4h - 2d)/a \Big\} \Big\{ [\sinh \pi (4h - r)/a]/\sinh \pi (4h + 2d - r)/a \Big\}$$

$$+ v^3 \log_e \Big\{ [\sinh \pi (r + 6h)/a]/\sinh \pi (r + 6h - 2d)/a \Big\} \Big\{ [\sinh \pi (6h - r)/a]/\sinh \pi (6h + 2d - r)/a \Big\}$$

$$- \ldots \Big) \quad \ldots\ldots (17)$$

as many terms being taken as the accuracy of the problem requires.

Equation (17) can be justifiably simplified by dropping the drain radius r in all sinh-terms except the term $\sinh \pi r/a$ [see KIRKHAM, 1950, footnotes, p. 659]. But the r in the numerator of (16) may not be dropped if the drain tube, as here assumed, is running full. If the drain tube is running nearly empty, however, dropping of the r in the numerator of (16) would be justifiable because the average hydraulic head over the inside of the drain tube would then be approximately zero.

Evaluation of the drain flow--In order to compute the drain flow Q--that is, the quantity of water flowing to unit length of drain in unit time--use is made, as in former work, of the fact that when r is small compared with d, h - d, and a, equation (15b) becomes, insofar as it applies to points in the immediate neighborhood of the drain, where $x^2 + y^2 \doteq r^2$

$$\phi_1 = f_o \log_e (\cosh 2\pi y/a - \cos 2\pi x/a) + \text{nearly const. terms}$$

so that [KIRKHAM, 1945]

$$Q = 4\pi K_1 f_o \quad \ldots\ldots (18)$$

Equation (18), in conjunction with (11), (16), and (17), constitutes a principal result of the analysis. It may be checked as follows: If $K_1 = 0$, then from (18) itself $Q = 0$, as it should. If $K_2 = 0$, then from (11) $v = 1$ and (18) reduces, with a little manipulation, to a known result [KIRKHAM, 1949, Eq. (15)]. If $K_1 = K_2$, then from (11), $v = 0$, and from (16) and (17), $Q = 4\pi K_1(t + d - r)/2 \log_e [\sinh \pi(2d - r)/a]/\sinh \pi r/a$, a result agreeing again with KIRKHAM'S work [1949, Eq. (15a)].

If K_1 is finite and K_2 is infinite there is no known case available with which to compare the present result.

Computation of the surface inflow distribution Q'--The quantity of water Q' entering a unit area of soil surface per unit time is, as an immediate consequence of Darcy's law applied at $y = d$

$$Q' = K_1(\partial\phi_1/\partial y)_{y=d} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (19)$$

Use of (15a) in (19) yields

$$Q' = (4\pi f_o K_1/a)M \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (20)$$

where

$$M = (\sinh 2\pi d/a)/(\cosh 2\pi d/a - X) + v\left\{[\sinh 2\pi(2h - d)/a]/[\cosh 2\pi(2h - d)/a - X] - [\sinh 2\pi(2h + d)/a]/[\cosh 2\pi(2h + d)/a - X]\right\} - v^2\left\{[\sinh 2\pi(4h - d)/a]/[\cosh 2\pi(4h - d)/a - X] - [\sinh 2\pi(4h + d)/a]/[\cosh 2\pi(4h + d)/a - X]\right\} + \ldots \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (21)$$

Formulas for the flow net; use of Kennelly's tables--The equipotentials in the flow net may be calculated by use of (15). The streamlines are most conveniently obtained by noting [KIRKHAM, 1945] that ϕ' in (1) is the real part of the complex potential w'

$$w' = \phi' + i\psi' = q \log_e \operatorname{vers} 2\pi z'/a \quad \ldots\ldots\ldots\ldots\ldots\ldots (22)$$

where

$$z' = x' + iy'$$

and that therefore the imaginary part ψ'

$$\psi' = 2q \tan^{-1}(\tanh \pi y'/a)(\cot \pi x'/a) \quad \ldots\ldots\ldots\ldots\ldots\ldots (23)$$

must be the form of the stream function corresponding to ϕ'.

Comparing now (1), (22), (23), (15b), and (15c), the stream functions ψ_1 and ψ_2 corresponding to ϕ_1 and ϕ_2 can be written down. They are

$$\psi_1 = 2f_o\left\{\tan^{-1}(\tanh \pi y/a)(\cot \pi x/a) - \tan^{-1}[\tanh \pi(y - 2d)/a](\cot \pi x/a) + \ldots\right\} \ldots (24a)$$

$$\psi_2 = 2(1 + v)f_o\left\{\tan^{-1}(\tanh \pi y/a)(\cot \pi x/a) - \tan^{-1}[\tanh \pi(y - 2d/a](\cot \pi x/a) + \ldots\right\} \ldots (24b)$$

The functions ψ_1 and ψ_2 will not be equal to each other at the interface of the two media. The stream functions $K_1\psi_1$ and $K_2\psi_2$ will, however, be equal at the interface. Additive constants are not needed on the right-hand side of (24a) and (24b).

Equations (15b), (15c), and (24a) and (24b) can be used for computing flow nets for the present problem. Use of these equations as such would, however, be extremely laborious. The flow nets can be calculated with greatly minimized effort, though there is still considerable work involved, by utilizing tables and charts of KENNELLY [1924, 1927]. These tables and charts are for hyperbolic functions of a complex variable and were originally prepared for solving problems in electrical engineering. If the author had been aware of the connection of Kennelly's tables with certain drainage problems, much labor could have been spared in computing previously worked out flow nets.

The functions of Kennelly which can be utilized here are those of the hyperbolic sine. The hyperbolic sine tables may be used because the versed-sine expression in the right-hand side of (22) can be transformed into terms of the hyperbolic sine. This is done, using known identities, as follows.

From DWIGHT [1947, formulas 400.17, 403.4, 408.10] one has, with $i = (-1)^{1/2}$

$$\text{vers } 2\pi z'/a = (1 - \cos 2\pi z'/a) = 2 \sin^2 \pi z'/a = 2 (-i \sinh i\pi z'/a)^2$$

Therefore, putting the last result in (22) one obtains

$$\phi' + i\psi' = q \log_e 2 (-i \sinh i\pi z'/a)^2 = 2q \log_e 2^{1/2} (-i \sinh i\pi z'/a) \qquad (25)$$

From (1), (15b), (15c), (25), and using the properties of the logarithms, one can now write down the desired formulas for the flow nets. They are

$$\begin{aligned} w_1 &= \phi_1 + i\psi_1 \\ &= 2f_o \Big\{ \log_e (\sinh i\pi z/a)/[\sinh i\pi (z - 2di)/a] + v \log_e \\ &\quad \sinh [i\pi (z + 2hi - 2di)/a]/[\sinh i\pi (z + 2hi)/a] \\ &\quad - v \log_e [\sinh i\pi (z - 2hi)/a]/[\sinh i\pi (z - 2hi - 2di)/a] \\ &\quad - v^2 \log_e [\sinh i\pi (z + 4hi - 2di)/a]/[\sinh i\pi (z + 4hi)/a] \\ &\quad + \ldots - (-1)^n v^{(n-1)} \log_e [\sinh i\pi (z - 2nhi + 2hi)/a]/ \\ &\quad [\sinh i\pi (z - 2nhi + 2hi - 2di)/a] - (-1)^n v^n \log_e \\ &\quad [\sinh i\pi (z + 2nhi - 2di)/a]/[\sinh i\pi (z + 2nhi)/a] \Big\} \\ &\quad - (-1)^n v^n (4\pi d/a) f_o + t + d \end{aligned} \qquad (26a)$$

$$\begin{aligned} w_2 &= \phi_2 + i\psi_2 \\ &= 2(1 + v) f_o \Big\{ \log_e (\sinh i\pi z/a)/\sinh i\pi (z - 2di)/a \\ &\quad - v \log_e [\sinh i\pi (z - 2hi)/a]/\sinh i\pi (z - 2hi - 2di)/a \\ &\quad + v^2 \log_e [\sinh i\pi (z - 4hi)/a]/\sinh i\pi (z - 4hi - 2di)/a \\ &\quad - \ldots \\ &\quad - (-1)^n v^{(n-1)} \log_e \sinh i\pi [z - (2n - 2)hi]/a/\sinh i\pi [z - (2n - 2)hi - 2di]/a \Big\} \\ &\quad - (-1)^n v^n (4\pi d/a) f_o + t + d \end{aligned} \qquad (26b)$$

When one uses Kennelly's tables, for numerical work with (26a) and (26b), Table X and Chart X, "Polar hyperbolic sines of a rectangular variable," should be chosen rather than the tables and charts for the rectangular variable. Use of the polar form is natural because, if one writes sinh (A + Bi) in the polar form R exp iL, where R is the modulus and L the amplitude (Kennelly uses the symbols r and γ for modulus and amplitude) one has

$$\log_e \sinh (A + iB) = \log_e R \exp iL = \log_e R + iL$$

Thus, the streamline component L for each logarithmic component in the right-hand side of (26a) and (26b) can be read directly from the tables, and the equipotential component $\log_e R$ can be obtained by taking the natural logarithm of Kennelly's tabulated value of R.

As mentioned previously, in order that the stream functions match at the interface, $K_1\psi_1$ and $K_2\psi_2$ should be plotted, or, more conveniently, ψ_1 should be plotted for region 1 and $(K_2/K_1)\psi_2$ for region 2. The latter procedure amounts to multiplication of the imaginary part of the bracket in (26b) by (1 - v) instead of (1 + v), because, as seen from (11), $K_2/K_1 = (1 - v)/(1 + v)$.

In drawing flow net lines at the interface y = - (h - d) the laws of refraction for streamlines and equipotentials are useful. These laws may be shown to be [TAYLOR, 1948, p. 186]

$$K_1 \cot E_1 = K_2 \cot E_2$$

$$K_1 \tan F_1 = K_2 \tan F_2$$

where E_1 is the angle of incidence and E_2 the angle of "refraction" for a streamline; and F_1 and F_2, the corresponding angles for an equipotential.

Results and discussion of results

Results as follows have been derived. Equations (15b) and (15c) give the hydraulic-head functions. (15b) gives the hydraulic head ϕ_1 for any point in the upper region of permeability K_1 (Fig. 1); and (15c) gives the hydraulic head for any point in the lower stratum of permeability K_2. The right-hand members of both of these equations are infinite series. The number of terms needed for practical results is specified by the inequality (15a). In (15b) and (15c) X is defined by (2), v by (11), f_0 by (16) and (17), and n by (15a). The quantities h, d, r, a, x, y, and t are indicated in Figure 1. The quantities ϕ_1 and ϕ_2 represent physically the distance above the plane of the drain centers to which water would stand in a piezometer tube the bottom of which is at the point (x, y) in the soil.

Equations (26a) and (26b) give the so-called complex potentials $w_1 = \phi_1 + i\psi_1$ and $w_2 = \phi_2 + i\psi_2$ corresponding to (15b) and (15c). The complex potentials have the property that they enable one to plot simultaneously lines of equal hydraulic head, ϕ_1 and ϕ_2, and streamlines ψ_1 and ψ_2. The quantity i in the w's is defined by $i = (-1)^{1/2}$, and need not be interpreted further than to say that the presence of i in (26a) and (26b) enables the simultaneous mathematical computation of the ϕ's and ψ's. Equations (26a) and (26b), and (15b) and (15c) involve K_1 and K_2 only through the ratio K_1/K_2. This is true because v of (11) may be written $v = (K_1/K_2 - 1)/(K_1/K_2 + 1)$. A physical interpretation is that piezometer levels will be the same for two soils regardless of K_1 and K_2, if K_1/K_2 is the same for both.

Equation (18), $Q = 4\pi K_1 f_0$, gives the drain flow rate per unit length. Here Q is the quantity of water entering a unit length of drain tube per unit time; f_0 is given, as before, by (16) and (17), and K_1 is the permeability of the upper soil stratum where the drains are located. If K_1 is in feet per day and the quantities in f_0 are in feet, Q will be in cubic feet per foot of drain tube per day.

A final result is (20), namely, $Q' = (4\pi f_0 K_1/a)M$. Here Q' is the quantity of water seeping into unit area of soil surface per unit time at a distance x from a vertical plane through a drain-tube axis; M is defined by (21); and the other quantities are as above. If K_1 is in feet per day, and all lengths involved are in feet, Q' will be in cubic feet per square foot per day.

Figures 3 and 4 show the flow nets for Case 1 when the drains are six inches in diameter, four feet deep, and 20 feet apart. The boundary separating the soils of different permeability is six feet below the soil surface. The flow net is shown only to a depth of 12 feet. The drain spacing of 20 feet is closer than commonly used. Use of close spacing simplifies the calculation, likewise the drawing and the reproduction, of a net. There is no loss of generality.

In Figure 3 the upper stratum is ten times as permeable as the lower stratum; and in Figure 4 the upper is 1/10 as permeable as is the lower. To make the situations vivid, the stratum of high permeability is designated "sand," and the one of low permeability, "clay." The distances in the figures are shown in feet. The flow nets are valid for other units of length.

The streamlines are labelled from 0 to 50. The 50-line is immediately above the drain tube; the 0-line, midway between the drains. A streamline may be thought of as the path of a bacterium moving with the water to a drain. The numbers on the streamlines are such that the difference in value for any two of them gives the percentage of flow entering the drain between these lines. Thus 25 per cent of the total flow to a drain passes through the region between the lines 30 and 5.

The equipotentials are labelled differently on the two sides of Figures 3 and 4. On the right-hand side the lines have values from 0 to 100; on the left-hand side, 0.25 to 4.25. A number on a line at the right gives the percentage of undissipated hydraulic head at points on the line. A number on an equipotential on the left gives the height, referred to the level of drain center, at which water will stand in a piezometer whose bottom touches the line in question when there is

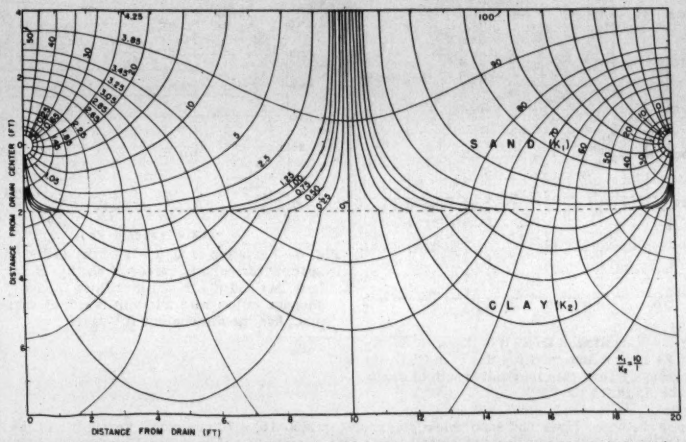


Fig. 3--Flow net for drain tubes of Figure 1 when permeability of the upper layer ("sand") is ten times that of the lower layer ("clay"); the values of hydraulic head 4.25, 3.85, etc., shown at the left, are for a surface layer of ponded water 0.25 ft thick; net is shown only to a depth of 12 ft

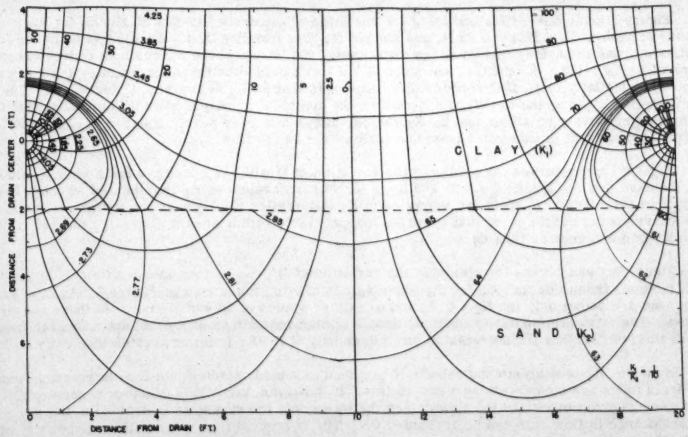


Fig. 4--Flow net; same as Figure 3 except that "sand" and "clay" are interchanged.

0.25 ft of surface water. As an example, any piezometers with ends on the 3.45 line will all show hydraulic heads of 3.45 ft above the drain centers.

Important features are brought out by the flow nets. When the sand is in the upper layer and clay below, more than 2(50-2.5) = 95 per cent of the flow occurs in the upper layer; whereas with

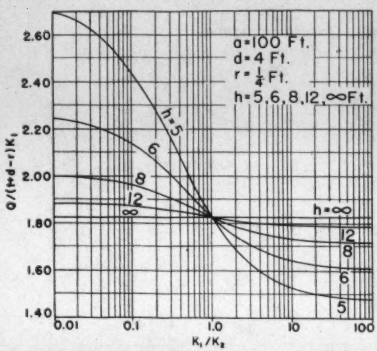


Fig. 5--Variation of $Q/(t+d-r)K_1$ with K_1/K_2; if K_1 is in ft/day, and $(t + d - r)$ in ft, Q, the seepage inflow rate into unit length of drain tube, is in ft3/day/ft

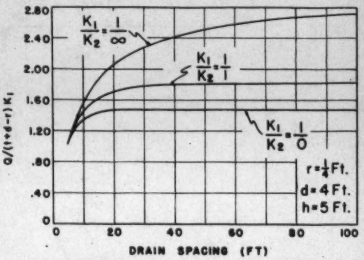


Fig. 6--Variation of $Q/(t + d - r)K_1$ with drain spacing for certain values of K_1/K_2; if K_1 is in ft/day and $(t + d - r)$ in ft, then Q, the seepage inflow rate into unit length of drain tube, has the dimensions ft^3/day/ft

clay in the upper layer and sand below, the result is 2(50-15) = 70 per cent. Very little of the flow moves along streamlines which fall lower than a depth 2h below the soil surface; about $0.25 \times 2 = 0.50$ per cent in Figure 3; about $2.5 \times 2 = 5$ per cent in Figure 4. Therefore, strata below 2h, regardless of their permeability, will have little effect on the total drainage rate. Hence one deduces the important result that the solution for the present problem is also the solution for multiply stratified soils for cases when the lower strata are not too near the upper stratum.

Figure 5 gives curves for obtaining the variation of the drain flux Q with K_1/K_2 for various values of h when d = 4 ft, r = 0.25 ft, and a = 100 ft. The quantity $Q/(t + d - r)K_1$ is taken as ordinate in order to have a dimensionless expression. To interpret the curves it is convenient to think of K_1 as being a constant. Then since $(t + d - r)$ can also be taken as constant, the curves become essentially plots of Q versus $1/K_2$. One sees that as K_2 decreases, Q decreases. The decrease is larger as the interface approaches the drain. A principal point of interest is that Q changes a relatively small amount as K_2 varies, unless h is very nearly equal to d. Thus the lower layer, except in extreme cases, has little effect on the flow.

Figure 6 gives curves for obtaining the variation of Q with the spacing a for $K_2 = 0$, 1 and ∞ for the case that r = 1/4 ft, d = 4 ft, and h = 5 ft. For concreteness K_1 is indicated as equal to unity, but the curves are valid for any value of K_1 if the ratios K_1/K_2 have the indicated values. The curves bring out the point that Q varies inappreciably with a when a is greater than 30 ft, unless K_2 is much greater than K_1.

Figure 7 gives curves for obtaining the variation of Q', the surface intake rate per unit area, with distance from a drain tube for the same values of r, d, and h used in Figure 6. As in Figure 6, curves are shown only for $K_2 = 0$, 1, and ∞. Other values of Q' will lie between these limiting values. The intake immediately over the drains is high regardless of K_2. At distances far from the drains, the surface intake remains fairly high only if K_2/K_1 is much greater than unity.

In all the above analysis and results it has been assumed, which is not true in practice, that the drain tubes are completely pervious to flow. If, however, the soil is of uniform permeability K_1 about the drain tubes and the flow enters the tubes only in cracks, as in drain tile, the resultant change in flow rate can be accounted for. The corrected flow rates will be given very approximately, if one replaces A in (16) by $A + S_1 + S_2$, where S_1 and S_2 can be obtained from the paper of KIRKHAM [1950]. The soil has been assumed to be isotropic. Anisotropy can be accounted for if desired [MUSKAT, 1937, pp. 225-227]. It is to be recognized in all the foregoing that the results can be applied in practical cases only insofar as the physical conditions assumed in setting up this problem are realized.

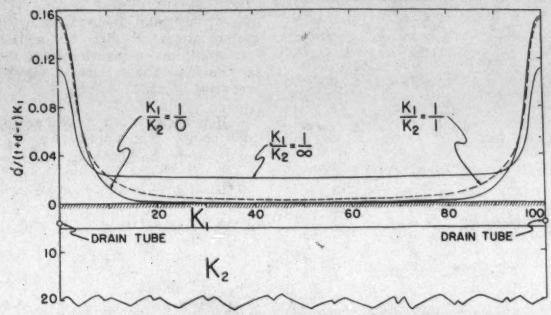


Fig. 7--Variation of $Q'/(t + d - r)K_1$ with distance from a vertical plane through a drain-tube axis; the case shown is for a = 100 ft, d = 4 ft, r = 0.25 ft, and h = 5 ft; if K_1 is in ft/day and (t + d - r) in ft, then Q', the surface seepage inflow rate per unit area, has the dimensions $ft^3/ft^2/day$

II - DRAINS BELOW THE SURFACE STRATUM

Analysis

Part II analyzes the problem of seepage into drain tubes in soil consisting of two layers of different permeabilities. The drains are in the lower layer, a layer extending downward to great depth. The geometry of the problem is indicated in Figure 8. As in Part I, where the drains are in the upper layer it is first assumed, in order to solve the problem, that an infinitely thick layer of soil of permeability K_0 (region 0) overlies the stratum of permeability K_1 (region 1). Later K_0 is set equal to ∞ and vanishes from the analysis.

Let θ_0, θ_1, and θ_2 be the hydraulic head (piezometric height) at any point, respectively, in region 0, 1, and 2. The reference level for hydraulic head is taken as the level of the axes of the drain tubes, y = 0, Figure 8. Since hydraulic head is a measure of potential energy of soil water, the θ's are potentials and it is easier to refer to them as such.

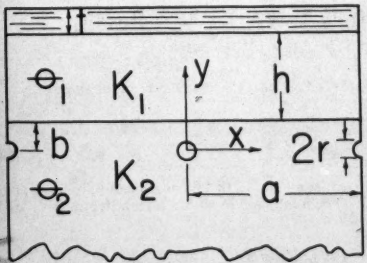


Fig. 8--Vertical section of field with ponded water and drain tubes; section is taken perpendicular to the drain tubes which are assumed to be equally spaced and horizontal

In order to evaluate the θ's, three sets of image drain tubes, one set for each potential, are required. The flow from and into these image drains, if they actually existed, would produce the actual flow of the problem. The needed sets of images are indicated in Figure 9. The image system for θ_0 is characterized by flow coefficients $j_0, j_1, j_2 \ldots$; for θ_1 by $m_0, m_1, m_2 \ldots$; $p_1, p_2, p_3 \ldots$; and for θ_2 by $s_0, s_1, s_2, \ldots$ The values of the flow coefficients shown in the figure will be derived later. The coefficient s_0 appearing in each of the values has the physical significance that $4\pi K_2$ times s_0 yields the quantity of water entering a unit length of drain tube per unit time. The image systems in Figure 9 differ from those in Part I in that flow coefficients at y = 2h, 4h, ..., -2h + 2b, - 4h + 2b, ..., are all zero. That the coefficients at these positions are all zero may be verified by assuming finite values for them and applying Conditions II and III below.

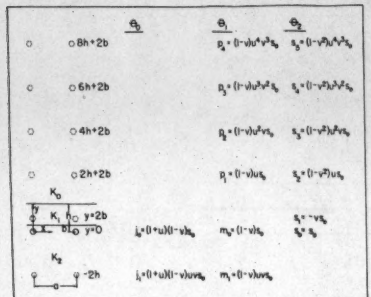


Fig. 9--Image array and flow coefficients corresponding to Figure 8; in final results K_0, which does not appear in Figure 8, is set equal to infinity and vanishes from the analysis

At this point the analysis becomes mainly mathematical. Readers not desiring to follow the details may pass directly to the Results and Discussion. The section "Checks" may be interesting to many.

Boundary conditions and evaluation of flow coefficients--The potentials θ_0, θ_1, and θ_2 must satisfy the following conditions.

$$\nabla^2\theta_0 = \nabla^2\theta_1 = \nabla^2\theta_2 = 0 \quad \text{. . . Condition (I)}$$

At the 0-1 interface

$$y = h + b \qquad \theta_0 = \theta_1 \quad \text{. . . . Condition (IIa)}$$

$$\left.\begin{matrix} y = h + b \\ K_0\partial\theta_0/\partial y = K_1\partial\theta_1/\partial y \end{matrix}\right\} \quad \text{. . . Condition (IIb)}$$

At the 1-2 interface

$$y = b \qquad \theta_1 = \theta_2 \quad \text{. . . . . Condition (IIIa)}$$

$$\left.\begin{matrix} y = b \\ K_1\partial\theta_1/\partial y = K_2\partial\theta_2/\partial y \end{matrix}\right\} \quad \text{. . . Condition (IIIb)}$$

At the surface of the soil next to the ponded water (a special case of Condition (IIa) when $K_0 = \infty$)

$$y = h + b \qquad \theta_1 = t + h + b \quad \text{. . . . . Condition (IV)}$$

At the upper surface of the drain (running full under no suction or back pressure)

$$y = r,\ x = o \qquad \theta_2 = r \quad \text{. . . . . Condition (V)}$$

At great depth

$$y \rightarrow -\infty \qquad \partial\theta_2/\partial y \rightarrow 0 \quad \text{. . . . . Condition (VI)}$$

On vertical planes passing through drain centers, but excluding those parts of the planes inside the drains

$$x = o, a, -a, \ldots, |y| \geq r \qquad \partial\theta_0/\partial x = \partial\theta_1/\partial x = \partial\theta_2/\partial x = 0 \quad \text{. . Condition (VII)}$$

The basic potential form θ' satisfying Conditions (I) and (VII) is [KIRKHAM, 1945]

$$\theta' = \log_e (\cosh 2\pi y'/a - \cos 2\pi x'/a \quad \text{. . . . . (27)}$$

where x' and y' are coordinates which may be referred to the axis of any real or image drain tube.

Using (27) and the abbreviation, as (2) of Part I

$$X = \cos 2\pi x/a \quad \text{. . . . . (28)}$$

where x is the ordinate in the (x, y) system of coordinates shown in Figures 8 and 9, one can, by inspecting Figure 9, write down, to within additive constants and to within terms linear in y, appropriate expressions for θ_0, θ_1, and θ_2 as follows

$$\theta_0 = j_0 \log_e (\cosh 2\pi y/a - X) + j_1 \log_e [\cosh 2\pi (y + 2h)/a - X]$$
$$+ j_2 \log_e (\cosh 2\pi (y + 4h)/a - X) + \ldots \quad \text{. . . . . (29)}$$

$$\theta_1 = m_0 \log_e (\cosh 2\pi y/a - X) + m_1 \log_e [\cosh 2\pi (y + 2h)/a - X]$$
$$+ m_2 \log_e (\cosh 2\pi (y + 4h)/a - X) + \ldots$$
$$+ p_1 \log_e [\cosh 2\pi (y - 2h - 2b)/a - X] + p_2 \log_e [\cosh 2\pi (y - 4h - 2b)/a - X] + \ldots \quad (30)$$

$$\theta_2 = s_0 \log_e (\cosh 2\pi y/a - X) + s_1 \log_e [\cosh 2\pi (y - 2b)/a - X]$$
$$+ s_2 \log_e [\cosh 2\pi (y - 2h - 2b)/a - X] + s_3 \log_e [\cosh 2\pi (y - 4h - 2b)/a - X] + \ldots \quad (31)$$

The j's, m's, p's, and s's in (29) to (31) can now be evaluated as in Part I, with the aid of Conditions (II) and (III). Introducing the abbreviations, as (10) and (11) of Part I

$$u = (K_1 - K_0)/(K_1 + K_0) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (32)$$

$$v = (K_1 - K_2)/(K_1 + K_2) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (33)$$

Eq. (33) being equivalent to

$$K_2/K_1 = (1 - v)/(1 + v)$$

one obtains the values listed in Figure 9.

For reasons previously given, K_0 is now set equal to ∞, with the following consequences: Eq. (32) yields $u = -1$; all the j's in Figure 9, since they include a factor $(1 + u)$ become zero; the right-hand member of (29) becomes zero to within an additive constant; the potential θ_0 needs no further consideration.

Attention is now directed to θ_1 and θ_2. Conditions (III) to (VI) remain to be satisfied. The details of required work need not be given here, since the reader who has followed through Part I will be able to work them out for himself. He will remember, as in Part I, that the approximation $\log_e [\cosh 2\pi (h + b)/a - \cos 2\pi x/a] = 2\pi (h + b)/a - \log_e 2$ is made if $(h + b) > a$, and the approximation $\log_e [\cosh 2\pi (3h + b)/a - \cos 2\pi x/a] = 2\pi (3h + b)/a - \log_e 2$, if $(3h + b) > a$, etc.; and that, therefore, the simplicity of derived results will depend upon the values of b, h, and a. There is an important difference in the analysis here as compared with Part I: Linear terms in y arise in order to satisfy Condition (VI).

Introducing a constant H which is the hydraulic head at the soil surface when covered by a layer of water of thickness t; and introducing terms Y_1 and Y_2, linear in y, these quantities being defined by

$$H = b + h + t \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (34)$$

$$Y_1 = 2\pi (K_2/K_1)(y - b - h)/a \quad \ldots\ldots\ldots\ldots\ldots\ldots (35)$$

$$Y_2 = 2\pi [y - b - (K_2/K_1)h]/a \quad \ldots\ldots\ldots\ldots\ldots\ldots (36)$$

one finds that potentials which satisfy Conditions (I), (III), (IV), (VI), and (VII) are as follows (Conditions (II) are no longer of concern; Condition (V) will be considered presently).

If
$$(h + b) > a \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (37a)$$

$$\theta_1 = (1 - v)\, s_0 \left\{ \log_e (\cosh 2\pi y/a - X) - [2\pi (h + b)/a - \log_e 2 - Y_1] \right\} + H \ldots\ldots (37b)$$

$$\theta_2 = s_0 \left\{ \log_e (\cosh 2\pi y/a - X) - v \log_e [\cosh 2\pi (y - 2b)/a - X] - (1 - v)[2\pi (h + b)/a - \log_e 2 - Y_2] \right\} + H \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (37c)$$

If
$$(3h + b) > a \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (38a)$$

$$\theta_1 = (1 - v)\, s_0 \left\{ \log_e (\cosh 2\pi y/a - X)/[\cosh 2\pi (y - 2h - 2b)/a - X] - v \log_e [\cosh 2\pi (y + 2h)/a - X] + v[2\pi (3h + b)/a - \log_e 2 - Y_1] \right\} + H \ldots\ldots\ldots\ldots (38b)$$

$$\theta_2 = s_o\Big\{\log_e(\cosh 2\pi y/a - X) - v\log_e[\cosh 2\pi(y - 2b)/a - X] - (1 - v^2)\log_e$$
$$[\cosh 2\pi(y - 2h - 2b)/a - X] + (1 - v)v[2\pi(3h + b)/a - \log_e 2 - Y_2]\Big\} + H \quad \ldots (38c)$$

If
$$(5h + b) > a \quad \ldots (39a)$$

$$\theta_1 = (1 - v)s_o\Big\{\log_e(\cosh 2\pi y/a - X)/[\cosh 2\pi(y - 2h - 2b)/a - X] - v\log_e[\cosh 2\pi$$
$$(y + 2h)/a - X]/[\cosh 2\pi(y - 4h - 2b)/a - X] + v^2\log_e[\cosh 2\pi(y + 4h)/a - X]$$
$$- v^2[2\pi(5h + b)/a - \log_e 2 - Y_1]\Big\} + H \quad \ldots (39b)$$

$$\theta_2 = s_o\Big\{\log_e(\cosh 2\pi y/a - X) - v\log_e[\cosh 2\pi(y - 2b)/a - X] - (1 - v^2)\log_e[\cosh 2\pi$$
$$(y - 2h - 2b)/a - X] + (1 - v^2)v\log_e[\cosh 2\pi(y - 4h - 2b)/a - X] - (1 - v)v^2$$
$$[2\pi(5h + b)/a - \log_e 2 - Y_2]\Big\} + H \quad \ldots (39c)$$

If k is an integer the results can be generalized:

If
$$[(2k + 1)h + b] > a \quad \ldots (40a)$$

$$\theta_1 = (1 - v)s_o\Big(\log_e(\cosh 2\pi y/a - X)/[\cosh 2\pi(y - 2h - 2b)/a - X]$$
$$- v\log_e[\cosh 2\pi(y + 2h)/a - X]/[\cosh 2\pi(y - 4h - 2b)/a - X]$$
$$+ v^2\log_e[\cosh 2\pi(y + 4h)/a - X]/[\cosh 2\pi(y - 6h - 2b)/a - X]$$
$$- \ldots$$
$$+ (-1)^{k-1}v^{k-1}\log_e\Big\{\cosh 2\pi[y + (2k - 2)h]/a - X\Big\}/[\cosh 2\pi(y - 2kh - 2b)/a - X]$$
$$+ (-1)^k v^k\log_e[\cosh 2\pi(y + 2kh)/a - X]$$
$$- (-1)^k v^k[2\pi(2kh + h + b)/a - \log_e 2 - Y_1]\Big) + H \quad \ldots (40b)$$

$$\theta_2 = s_o\Big\{\log_e(\cosh 2\pi y/a - X) - v\log_e[\cosh 2\pi(y - 2b)/a - X]$$
$$- (1 - v^2)\log_e[\cosh 2\pi(y - 2h - 2b)/a - X]$$
$$+ (1 - v^2)v\log_e[\cosh 2\pi(y - 4h - 2b)/a - X]$$
$$- (1 - v^2)v^2\log_e[\cosh 2\pi(y - 6h - 2b)/a - X]$$
$$+ \ldots$$
$$+ (-1)^k(1 - v^2)v^{k-1}\log_e[\cosh 2\pi(y - 2kh - 2b)/a - X]$$
$$- (-1)^k(1 - v)v^k[2\pi(2kh + h + b)/a - \log_e 2 - Y_2]\Big\} + H \quad \ldots (40c)$$

Although (40a) appears to set a limit of accuracy on θ_1 and θ_2 in the general case, this is not true because if k is taken sufficiently large, that is to say, if a sufficient number of terms are taken in (40b) and (40c), then any specified degree of exactness in θ_1 and θ_2 may be obtained.

Calculation of s_o and the drain flow--Using Condition (V), and Eq. (34) and (36), and (37c), (38c), (39c), and (40c), one finds

$$s_o = (b + h + t - r)/L \quad \ldots (41)$$

where, if $(h + b) > a$

$$L = -\Big(\log_e(\cosh 2\pi r/a - 1) - v\log_e[\cosh 2\pi(r - 2b)/a - 1]$$
$$- (1 - v)\Big\{2\pi[2b - r + h(1 + K_2/K_1)]/a - \log_e 2\Big\}\Big) \quad \ldots (41a)$$

and if $3h + b > a$

$$L = -\Big(\log_e(\cosh 2\pi r/a - 1) - v\log_e[\cosh 2\pi(r - 2b)/a - 1] - (1 - v^2)\log_e[\cosh 2\pi(r - 2h - 2b)/a - 1] + (1 - v)v\Big\{2\pi[2b - r + h(3 + K_2/K_1)]/a - \log_e 2\Big\}\Big) \quad (41b)$$

and if $(5h + b) > a$

$$L = -\Big(\log_e(\cosh 2\pi r/a - 1) - v\log_e[\cosh 2\pi(r - 2b)/a - 1] - (1 - v^2)\log_e [\cosh 2\pi(r - 2h - 2b)/a - 1] + (1 - v^2)v\log_e[\cosh 2\pi(r - 4h - 2b)/a - 1] - (1 - v)v^2\Big\{2\pi[2b - r + h(5 + K_2/K_1)]/a - \log_e 2\Big\}\Big) \quad (41c)$$

and if $(2k + 1)h + b > a$

$$L = -\Big(\log_e(\cosh 2\pi r/a - 1) - v\log_e[\cosh 2\pi(r - 2b)/a - 1] - (1 - v^2)\log_e [\cosh 2\pi(r - 2h - 2b)/a - 1] + (1 - v^2)v\log_e[\cosh 2\pi(r - 4h - 2b)/a - 1] - (1 - v^2)v^2\log_e[\cosh 2\pi(r - 6h - 2b)/a - 1] + \ldots + (-1)^k(1 - v^2)v^{k-1}\log_e[\cosh 2\pi(r - 2kh - 2b)/a - 1] - (-1)^k(1 - v)v^k\Big\{2\pi[2b - r + h(2k + 1 + K_2/K_1)]/a - \log_e 2\Big\}\Big) \quad (41d)$$

For reasons given below (17) of Part I, one sees that (41a) and (41b) can be justifiably simplified by dropping r in all terms except $\cosh 2\pi r/a - 1$. In addition, simplification will result through use of the identities $\cosh A = \cosh(-A)$ and $\cosh 2A - 1 = 2\sinh^2 A$.

The quantity Q of water entering unit length of drain tube per unit time may be obtained as was done before (18) of Part I. The result is

$$Q = 4\pi K_2 s_o \quad (42)$$

where s_o is given by (41).

Formulas for flow nets--As in Part I, complex potentials corresponding to θ_1 and θ_2 of (37) to (40) can be written down in terms of hyperbolic sines. From these potentials flow nets for various values of the parameters can be calculated using charts and tables of KENNELLY [1927, 1924]. To obtain the needed formulas one recalls, from Part I, (1) and (25), the relations, true for any $z' = x' + iy'$, (using the notation Re = "real part of")

$$\log_e(\cosh 2\pi y'/a - \cos 2\pi x'/a) = \mathrm{Re}\,[2\log_e 2^{1/2}(-i\sinh i\pi z'/a)] \quad (43)$$

$$y' = \mathrm{Re}(-iz') \quad (44)$$

If one now uses (35), (36), and (44), and takes

$$z = x + iy \quad (45)$$

to obtain

$$Y_1 = \mathrm{Re}\,2\pi(K_2/K_1)(-iz - b - h)/a \quad (46)$$

$$Y_2 = \mathrm{Re}\,2\pi[-iz - b - (K_2/K_1)h]/a \quad (47)$$

then one has from (40), and (43) to (47), these results.

If

$$[(2k + 1)h + b] > a \quad (48a)$$

$$w_1 = (1 - v)\, s_o \Big(2 \log_e(\sinh i\pi z/a)/\sinh i\pi(z - 2hi - 2bi)/a$$
$$- 2v \log_e[\sinh i\pi(z + 2hi)/a]/\sinh i\pi(z - 4hi - 2bi)/a$$
$$+ 2v^2 \log_e[\sinh i\pi(z + 4hi)/a]/\sinh i\pi(z - 6hi - 2bi)/a$$
$$- \ldots$$
$$+ 2(-1)^{k-1} v^{k-1} \log_e\Big\{\sinh i\pi[z + (2k - 2)hi]/a\Big\}/\sinh i\pi(z - 2khi - 2bi)/a$$
$$+ 2(-1)^k v^k \log_e 2^{1/2}[-i \sinh i\pi(z - 2khi)/a]$$
$$- (-1)^k v^k [2\pi(2kh + h + b)/a - \log_e 2 - 2\pi(K_2/K_1)(-iz - b - h)/a]\Big) + H \quad \ldots\ldots (48b)$$

$$w_2 = s_o \Big(2 \log_e 2^{1/2}(-i \sinh i\pi z)/a - 2v \log_e 2^{1/2}[-i \sinh i\pi(z - 2bi)/a]$$
$$- 2(1 - v^2) \log_e 2^{1/2}[-i \sinh i\pi(z - 2hi - 2bi)/a] + 2(1 - v^2) v \log_e 2^{1/2}$$
$$[-i \sinh i\pi(z - 4hi - 2bi)/a] - 2(1 - v^2) v^2 \log_e 2^{1/2}[-i \sinh i\pi(z -$$
$$6hi - 2bi)/a] + \ldots + (-1)^k (1 - v^2) v^{k-1} \log_e 2^{1/2}[-i \sinh i\pi(z - 2khi - 2bi)$$
$$/a] - (-1)^k (1 - v) v^k \Big\{2\pi(2kh + h + b)/a - \log_e 2 - 2\pi[-iz - b - (K_2/K_1)h]/a\Big\}\Big) + H \ldots (48c)$$

The imaginary parts of w_1 and w_2 give the stream functions in regions 1 and 2, but these stream functions will not yield continuous values at $y = h$ unless w_1 is multiplied by K_1 and w_2 by K_2. The real parts θ_1 and θ_2 of w_1 and w_2 are not to be multiplied by K_1 and K_2, however.

Formulas (48) are not valid for $k = 0$. The correct formulas in this case may be written down by inspection of (37), and (43) to (47).

In using Kennelly's tables to obtain the imaginary parts of w_1 and w_2, his values must be expressed in radians. This was not necessary in Part I. Also, for numerical work with (48b) and (48c) the relation is needed [see DWIGHT, 1947, formula 408.04], $\log_e(-i) = \log_e \exp(-i\pi/2) = -i\pi/2$.

Formula for the inflow rate per unit area of the soil surface.--The surface inflow rate Q' per unit area is obtained as a function of $X = \cos 2\pi x/a$ by differentiating (40b) with respect to y, setting y in the result equal to $(h + b)$ and multiplying the answer by K_1. The result, after some simplification, is

$$Q' = K_1(2\pi/a)(1 - v)\, s_o \Big([2 \sinh 2\pi(h + b)/a]/[\cosh 2\pi(h + b)/a - X]$$
$$- v[2 \sinh 2\pi(3h + b)/a]/[\cosh 2\pi(3h + b)/a - X]$$
$$+ v^2 [2 \sinh 2\pi(5h + b)/a]/[\cosh 2\pi(5h + b)/a - X]$$
$$- \ldots$$
$$+ (-1)^{k-1} v^{k-1} \Big\{2 \sinh 2\pi[(2k - 1)h + b]/a\Big\}/\Big\{\cosh 2\pi[(2k - 1)h + b]/a - X\Big\}$$
$$+ (-1)^k v^k \Big\{\sinh 2\pi[(2k + 1)h + b]/a\Big\}/\Big\{\cosh 2\pi[(2k + 1)h + b]/a - X\Big\}$$
$$+ (-1)^k v^k K_2/K_1\Big) \quad \ldots\ldots (49)$$

Checks

There are a number of tests for checking the validity of the formulas derived above. The drain-flow equation is probably of greatest interest. Let us see what happens to (42) (in which s_o is given by (41) to (41d))in the three cases: $K_2 = 0$; $K_2 = K_1$; and $K_2 = \infty$. In each case K_1 is to be considered finite.

If $K_2 = 0$, then from (42) directly (since s_o is finite for $K_2 = 0$) $Q = 0$, as it should.

If $K_2 = K_1$, then from (33) $v = 0$ and from (41d)

$$L = -\log_e(\cosh 2\pi r/a - 1)/[\cosh 2\pi(r - 2h - 2b)/a - 1] = 2\log_e[\sinh \pi(2b + 2h - r)/a]/\sinh \pi r/a$$

so that

$$Q = 2\pi K(b + h + t - r)/\log_e[\sinh \pi(2b + 2h - r)/a]/\sinh \pi r/a$$

agreeing with results independently obtained elsewhere [Part I, equation preceding (19); and KIRKHAM, 1949, (15a)], as it should.

If $K_2 = \infty$, the most interesting check is obtained; there can be no drop in head due to friction loss of water flowing in medium 2. Therefore, all the water in medium 2 is at constant hydraulic head, namely, r (since by hypothesis the drains are running full with no back pressure or suction). Now the difference in hydraulic head between the soil surface and the drain outlet is h + b + t - r; and the length of soil column over which this head is dissipated when $K_2 = \infty$ is h. Therefore, if one considers a strip of area a units long and 1 unit wide, one can write down immediately by Darcy's law

$$Q = K_1 a(b + h + t - r)/h \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (50)$$

In (50), (b - r) may be considered a suction head at the base of the soil column. This suction exists because by hypothesis the space beneath the soil is kept full of water, which empties at the level of the top of the drains at a rate just equal to the seepage rate through the soil.

To see whether (50) can be obtained from (42), one first puts (corresponding to $K_2 = \infty$) $v = -1$ in (41d). Then all terms except the first two and the last one are zero. The remaining first two terms are negligible compared with the last because when K_2/K_1 approaches infinity, the first two terms remain finite. Equation (41d) thus yields (remembering that k in the braces of the last term stays finite for any specified accuracy of results)

$$L = (-1)^k (2)(-1)^k \left\{(2\pi/a)(K_2/K_1)h\right\}$$

that is, since $(-1)^k \cdot (-1)^k = +1$, regardless of k

$$L = (4\pi/a)(K_2/K_1)h$$

Putting this value of L in (41) and the result in (42), one obtains (50) immediately, the required relation.

Results and discussion

Figure 10 shows the flow net corresponding to Figure 8 when $K_1/K_2 = 10$, h = 3 ft, b = 1 ft, and $a = 20\pi/3$ ft. The net was computed using (40) with the integer k (not to be confused with permeability) equal to unity. With k = 1, (40a) is not satisfied; therefore, a slight smoothing of the curves near y = h + b was necessary. The drain spacing $20\pi/3 = 20.94$ ft was chosen instead of 20 ft in order to avoid interpolation in Kennelly's tables. To make the situation vivid the mediums of high and low permeability are labelled "sand" and "clay" respectively. The streamlines are labelled 50, 40, ..., 0. The difference between any pair of streamlines is the percentage of the total seepage flow passing between these lines. The 30-streamline begins at a horizontal distance 2 ft from a vertical plane through a drain center. Therefore, 2 × (50-30) = 40 pct of the total flow entering a drain tube passes through a strip of soil 4 ft wide over the length of the drain. On the left-hand half of the figure the equipotentials are labelled in feet of hydraulic head and are for the case that the drain tube is running full with zero back pressure and the soil is covered with 0.25 ft of surface water. Therefore, the equipotentials which coincide with the drain tube and soil surface are labelled respectively 0.25 and 4.25. On the right-hand half of the figure the equipotentials are labelled in per cent of undissipated hydraulic head; at the drain 0, at the soil surface 100. The streamlines diverge as they pass from the sand into the clay. This divergence tends to cut down the head loss in the clay but most of the head loss occurs there anyway. For example, on streamline 10 the head loss in the sand is 4.25 - 4.15 = 0.10 ft; whereas the head loss in the clay is 4.25 - 0.10 = 4.15 ft. Immediately over the drain tube the head loss in the sand (4.25 - 3.65 = 0.60 ft) is proportionally greatest, but it is still small compared to the loss (3.65 - 0.25 = 3.40 ft) in the clay. Thus, one may say that the lower layer controls the flow. A flow net with the sand and clay interchanged is not shown because with sand underlying clay, drain tubes would, in practice, generally take water from the sand faster than the clay could supply it. Thus, air space would develop in the sand, and water entering the sand from the clay would do so by a

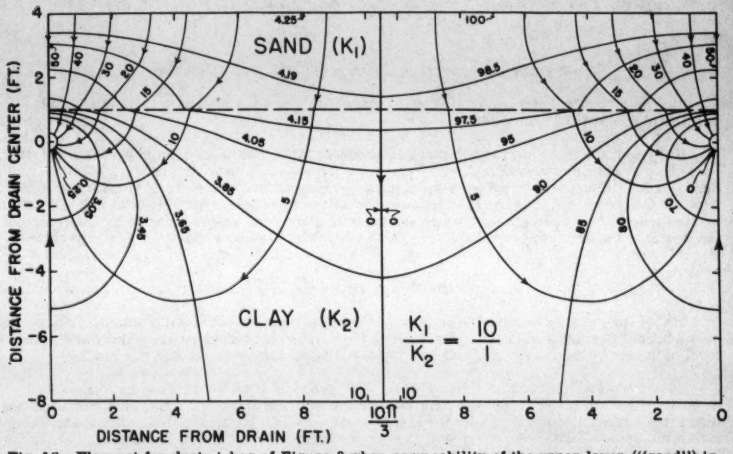


Fig. 10--Flow net for drain tubes of Figure 8 when permeability of the upper layer ("sand") is ten times that of the lower layer ("clay"); the values of hydraulic head, 4.25, 4.19, etc., shown at the left, are for a surface layer of ponded water 0.25 ft thick; net extends downward to infinity but is shown only to a depth of 12 ft

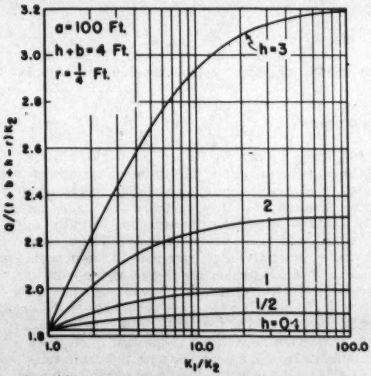


Fig. 11--Variation of $Q/(t + b + h - r)K_1$ with K_1/K_2; if K_1 and K_2 are in ft/day and r, t, h, b, and a of Figure 8 are in feet, then Q, the seepage inflow rate into unit length of drain tube, will be in $ft^3/day/ft$

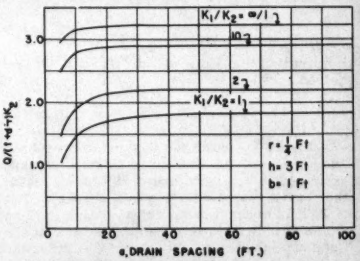


Fig. 12--Variation of $Q/(t + b + h - r)K_2$ with the drain spacing a for several values of K_1/K_2; units are as for Figure 11

process akin to dripping; that is, the streamlines in the clay would be vertical and the theory here developed would not be needed.

Figure 11, calculated from (42) and (41), is a set of curves showing the relation between $Q/(t + b + h - r)K_2$ and K_1/K_2 for several values of h, when h + b, the drain depth, has the constant

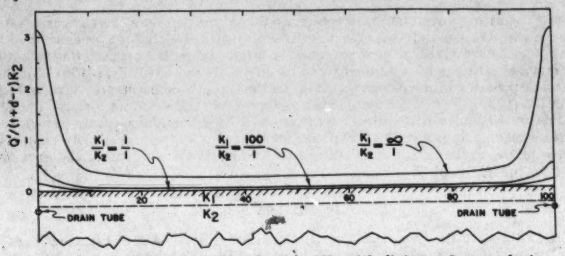


Fig. 13--Variation of $Q'/(t + b + h - r)K_2$ with distance from a drain tube for r = 0.25 ft, h = 3 ft, b = 1 ft, a = 100 ft; when K_1 and K_2 are in ft/day and t is in feet, then Q', the volume of water entering the soil surface per unit area in unit time, will be in $ft^3/ft^2/day$

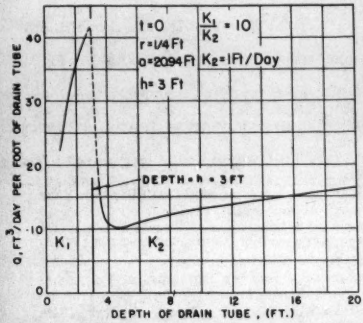


Fig. 14--Variation of drain flow Q with depth of drain tube in a two-layered soil; surface layer is 3 ft thick and of permeability ten feet per day; subsurface layer extends to great depth and is of permeability one foot per day

value four feet; the drain spacing is 100 ft; and the drain diameter, 0.5 ft. Here Q is the inflow rate per unit length of drain tube and $(t+b+h-r)$ is the driving hydraulic head. For a fixed value of $(t + b + h - r)K_2$, Q increases as K_1 increases and also, as h increases. Values for K_1/K_2 less than unity are not given in the figure, nor in further figures, for the practical reason mentioned in the preceding paragraph.

Figure 12 shows the variation of $Q/(t + b + h - r)K_2$ with drain spacing a for several values of K_1/K_2 when the drain depth is four feet and r, b, and h of Figure 8 are 0.25 1, and 3 ft respectively. For drain spacings greater than about 20 ft the percentage increase in Q due to an increase in K_1/K_2 is practically constant. For example, at a spacing a = 20 ft, increasing K_1 from one to ∞ while holding K_2 at the constant value unity, say, increases $Q/(t + b + h - r)K_2$ from 1.71 to 3.20; whereas for a = 100 ft the values are 1.83 and 3.23.

Figure 13 presents curves of $Q'/(t + b + h - r)K_2$ versus distance from a drain tube, for the geometry indicated. Here Q' is the volume of water entering unit area of soil per unit time at the soil surface. The curves, which were computed with the aid of (49), show that the flow midway between drains is a very small proportion of that entering over the drains, even when the ratio K_1/K_2 is large.

Figure 14 is a plot of Q versus drain depth for a soil which is ten times more permeable in the upper three feet than in the soil below. The drain diameter is 0.5 ft, and the spacing, 100 ft. To obtain the curve, (18), (16), (17), and (11) of Part I, and (42), (41), and (33) of Part II were used. Since the theory breaks down as the drain tube passes through the interface the portion of the curve in this region is estimated, and indicated thus, by a dashed line. From physical considerations (and it can also be shown analytically) the dashed curve will not be far in error. The flow rate increases rapidly with depth until the layer of low permeability is reached. As the drain tube passes into the lower layer the flow falls off abruptly and decreases until the drain tube is about five feet deep. The curve then rises nearly linearly, but at a slow rate compared to the rate in the upper medium.

In all the above it is to be remembered that the results are valid only for the assumed boundary conditions. The soil has been assumed to be uniform in each of the two layers, to be water-saturated to the soil surface, and to contain drain tubes which are, or behave as if, completely porous. LUTHIN and GASKELL [1950] have considered seepage when a soil is of higher permeability immediately above and around a drain tube than in the adjacent soil. There is no analytical theory to

cover the case of a falling water table. When drain tubes are porous at circumferential openings, as in farm drain tile, the constricting effect on flow may be accounted for as described in Part I. When the drain tubes have circular perforations for water entry, the constricting effect of the perforations may be accounted for as described by SCHWAB and KIRKHAM [1951]. If the soil contains layers of three or more permeabilities the theory will be extremely involved (compare work of HUMMEL [1929]). The flow nets shown here reveal that strata of a third, fourth, or higher permeability will have little effect on the drain flow unless these strata are close to the level of the drain tubes and unless the additional strata are of high permeability compared to the stratum containing the drain tubes. It is not considered worthwhile to extend the present theory to three or more permeabilities.

References

DWIGHT, H. B., Tables of integrals and other mathematical data, Macmillan, New York, 1947.

HUMMEL, J. N., Der scheinbare spezifische Widerstand, Zs. Geophys., v. 5, pp. 89-104, 1929 (or Handbuch der Exp. Physik, v. 25, pt. 3, Geophysik, especially pp. 414-415, Akad. Verlag, Leipzig, 1930).

JEANS, J., The mathematical theory of electricity and magnetism, 5th ed., University Press, Cambridge, Eng., 1933.

KENNELLY, A. E., Chart atlas of complex hyperbolic and circular functions, Harvard Univ. Press, Cambridge, Mass., 1924.

KENNELLY, A. E., Tables of complex hyperbolic and circular functions, 2nd ed., Harvard Univ. Press, Cambridge, Mass., 1927.

KIRKHAM, DON, Artificial drainage of land, streamline experiments, the artesian basin, III, Trans. Amer. Geophys. Union, v. 26, pp. 393-407, 1945.

KIRKHAM, DON, Flow of ponded water into drain tubes in soil overlying an impervious layer, Trans. Amer. Geophys. Union, v. 30, pp. 369-386, 1949.

KIRKHAM, DON, Potential flow into circumferential openings in drain tubes, J. Applied Physics, v. 21, pp. 655-660, 1950.

LUTHIN, J. N., and R. E. GASKELL, Numerical solutions for tile drainage of layered soils, Trans. Amer. Geophys. Union, v. 31, pp. 595-602, 1950.

MUSKAT, M., The flow of homogeneous fluids through porous media, McGraw-Hill, New York, 1937 [or second printing, J. W. Edwards, Inc., Ann Arbor, Mich., 1946].

SCHWAB, G. O., and D. KIRKHAM, The effect of circular perforations on flow into subsurface drain tubes, pt. II, Experiments and results, Agricultural Eng., v. 32, pp. 270-274, 1951.

STEFANESCO, S., and C. and M. SCHLUMBERGER, Sur la distribution électrique potentielle autour d'une prise de terre ponctuelle dans un terrain à couches horizontales, homogènes et isotropes, J. Phys. et Rad., sér. 7, v. 1, no. 4, pp. 132-141, 1930.

TAYLOR, D. W., Fundamentals of soil mechanics, John Wiley and Sons, Inc., New York, 1948.

Iowa State College,
Ames, Iowa

(Manuscript received September 6, 1950; presented in part at the Twenty-Ninth Annual Meeting, Washington, D. C., April 22, 1948; open for formal discussion until November 1, 1951.)

Transactions, American Geophysical Union Volume 32, Number 3 June 1951

POROSITY FACTOR FOR CASE OF LAMINAR FLOW THROUGH GRANULAR MEDIA

Joseph B. Franzini

Abstract--The resistance coefficient of flow through granular media depends on the porosity of the medium as well as the Reynolds number of the flow. There is disagreement as to the functional relationship between porosity and resistance coefficient, hence a series of carefully conducted permeability tests was made on randomly packed and systematically packed media using a variable head permeameter. The test results indicated that the relationship between porosity and resistance coefficient for laminar flow through granular media is represented best by the Fair-Hatch expression $(1-a)^2/a^3$ when compared with other factors that appear in the literature.

Introduction--Flow through granular media is very complicated and cannot be analyzed readily because of immeasurable quantities such as particle shape and size distribution. An element of fluid follows a very tortuous path through the pore passages of a medium. Physically the flow through granular media is not analagous to flow in pipe lines; however, the hydraulic gradient can be represented by an expression of similar form

$$(h_L/\ell) = \psi\,(1/d)(V^2/2g) \qquad (1)$$

where (h_L/ℓ) is the hydraulic gradient, ψ the medium resistance coefficient, d a parameter of particle size and shape, and V the rate of flow per unit of cross-sectional area of medium. It can be shown by dimensional analysis that ψ depends not only on the Reynolds number of the flow but also on the porosity of the medium. At low Reynolds numbers the flow through granular media is essentially laminar and resistance is due to viscous action of the fluid while at high Reynolds numbers the flow is essentially turbulent and resistance is due to inertial effects. This discussion will be confined to laminar flow. The natural flow of water and oil through sand and gravel usually falls in this category.

BAKHMETEFF [1937], ROSE [1945], and others have experimental verification that flow through granular media is laminar if Reynolds number is less than five. For the case of laminar flow the medium resistance coefficient may be expressed by

$$\psi = (\text{Constant}/\underline{R})[F\,(a)] \qquad (2)$$

where $\underline{R}$ is the Reynolds number of the flow and [F (a)] the porosity factor. $\underline{R}$ is expressed by dV/ν where d is the effective diameter of the particles, V is the velocity of flow (that is, the flow rate divided by the gross cross-sectional area), and ν is the kinematic viscosity of the fluid. Approximately a dozen porosity factors have been proposed in the literature. Some are based on analysis, others on experiment. Several of the proposed porosity factors are given in Table 1. They vary quite a bit with one another. For example, if the porosity of a given medium is changed from 40 to 36 pct, the FAIR-HATCH [1933; KOZENY, 1927] porosity factor increases 55 pct while the Bakhmeteff factor increases only 15 pct. In order to determine which of the porosity factors is the most reliable, two groups of permeability tests were conducted, one on randomly packed media such as sand and lead shot, the other on aggregations of uniform spheres some of which were systematically packed.

Table 1--Porosity factors for laminar flow

Porosity factor	Source	Remarks
$1/a^5$ or $1/a^6$	MAVIS and WILSEY, 1936	From experiments on sand
$(1-a)^2/a^3$	KOZENY, 1927	From analysis
	FAIR and HATCH, 1933	From analysis; confirmed by experiments
$1/a^{3.3}$	SLICHTER, 1897	From analysis
$1/a^n$, $n = \phi(a)$	ROSE, 1945	From experimental data
$1/a^4/3$	BAKHMETEFF, 1937	From analysis; confirmed by experiments

Scope of permeability tests--In the first group of tests, those on randomly packed media, porosities ranging from 34 to 42 pct were obtained by varying the degree of agitation of the media. More extreme values of porosity are possible in the case of systematically packed uniform spheres, however: 25.95 pct porosity for cubic tight (rhombohedral) packing and 47.64 pct porosity for cubic loose packing. Tests on granular media with unusually low and high porosities were considered desirable as previous work had been confined almost entirely to the 34 to 42 pct range of porosities. Hence, the second group of tests involved media with cubic tight and cubic loose packing.

Tests of randomly packed media--A variable head permeameter was used exclusively in all tests. The chief advantage of such a piece of equipment is its simplicity of construction and ease of operation. The error introduced by the unsteadiness of the flow is negligible providing the rate of change of head is small. An outstanding advantage of the variable head permeameter over the constant head type is superior control over air bubbles. The variable head permeameter used in the first group of tests consisted of a two-inch diameter lucite tube 52 inches long. The test sample was supported on an interchangeable wire screen and could be observed before, during, and after test. The media tested in this group were Ottawa 20-30 mesh sand, no. 9 lead shot, and a fine angular sand. Water and SAE 10 oil were used as liquids. Information pertinent to these tests is presented in Table 2.

Table 2--Data on randomly packed media

Test sample	Average particle diameter	Liquid	Porosity range
	in		pct
Ottawa 20-30 sand	0.0276	Water	34-41
Ottawa 20-30 sand	0.0276	SAE 10 oil	35-42
No. 9 lead shot	0.0818	SAE 10 oil	39-42
Fine angular sand	0.0067	Water	35-42

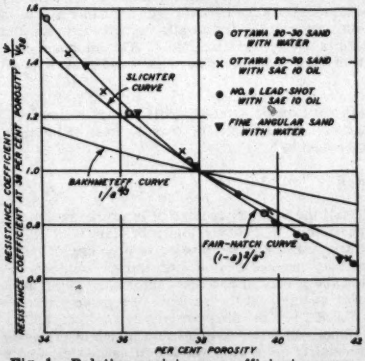


Fig. 1--Relative resistance coefficient versus porosity for randomly packed media

After the liquid was siphoned into the permeameter the test sample was slowly poured into the tube. Great care was taken that a minimum of air was entrained in the sample. Even though the particles fell through a four-foot column of liquid, segregation was negligible as the particles for any given test were of almost uniform size. The length of test section was about a foot, and during a run the head fell from 3.5 to 1.5 ft. Porosity of the media was adjusted by tapping the tubes and twisting them vigorously back and forth. The temperature of the liquid was recorded before each run and its viscosity was taken from a viscosity-temperature curve. The results of this group of tests are plotted in Figure 1. A resistance coefficient of unity was assumed at 38 pct porosity. The results agreed favorably with the Fair-Hatch relationship.

Tests of systematically packed media--Permeability tests were conducted on media consisting of 0.250-inch diameter steel ball bearings. These were packed in different geometric arrangements, cubic tight packing and cubic loose packing. They were also packed in random manner for basis of comparison. Special apparatus was required to perform these tests, namely, a square tube variable head permeameter of lucite with internal dimensions three inches by three inches in cross section and 50 inches long. The lower end of the tube was attached to a brass fitting which was threaded at its other end to receive a plug which contained the inlet pipe. The permeameter was supported by a wooden framework. A photograph of the apparatus is shown in Figure 2.

The upper end of the tube was capped with a plate in which a stopcock was threaded. A rubber hose connected the stop-cock to a vacuum pump. Two special loading boxes were constructed to hold the spheres. After the spheres were packed, the loading box was placed in the brass fitting

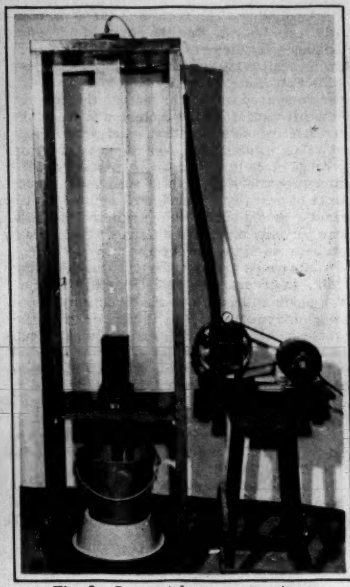


Fig. 2--Square tube permeameter

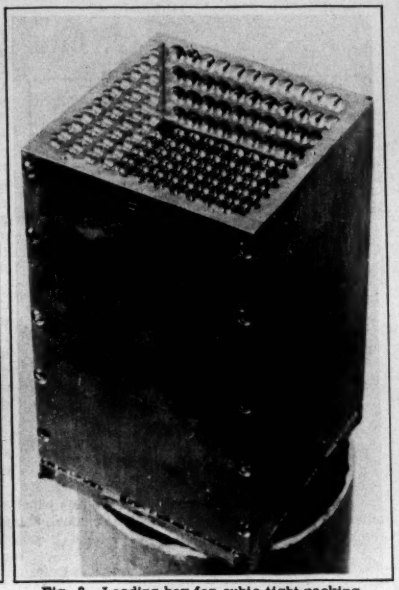


Fig. 3--Loading box for cubic tight packing

and securely bolted in place. The spheres were held in the box by no. 4 wire-mesh screens whose resistance to flow was found to be negligible. Figure 3 shows the loading box for cubic tight packing of spheres. In this case boundary conditions were satisfied by placing spheres in the hemispherical holes which were drilled in the side walls of the loading box. Since the corner quarter-spheres were omitted, the resulting aggregation had a porosity of 27.1 pct.

A very viscous oil, "Alta Visc 50," was used in these tests to maintain laminar flow conditions. The oil was drawn up into the tube by means of a vacuum pump and then permitted to stand until the air bubbles had risen up out of it. Care was taken that the temperature was constant during a run. The relative viscosity of the oil was determined by dropping a 0.125-inch diameter steel sphere into the oil just before test. To make a run the plug was removed and times were recorded as the head fell. In addition to testing the spheres in the tightest and loosest conditions, several tests were conducted with the spheres in random packing. Slight corrections for wall effect had to be made in all cases. Information pertinent to the media tested in this group is presented in Table 3. The results are plotted in Figure 4.

Table 3--Data on Aggregations of 0.250-inch diameter steel ball bearings

Type of packing	Porosity	Length of test section
	pct	in
Cubic	47.6	5.50
Very loose random	43.7	5.08
Loose random	41.0	5.50
Random	39.9	5.50
Tight-random	38.6	5.50
Rhombohedral	27.1	5.38

The test results of this group follow the trend of the Fair-Hatch curve. The rather large discrepancy with the Fair-Hatch curve at 47.64 pct porosity is caused by the fact that this medium had straight uninterrupted passages through it and hence its resistance to flow was decreased. The results check closely with those of GREEN [1949] who performed tests on similar aggregations using a steady flow system with nitrogen as the fluid. His tests were over a wide range of Reynolds numbers that included both laminar and turbulent flow. His results are also shown on Figure 4.

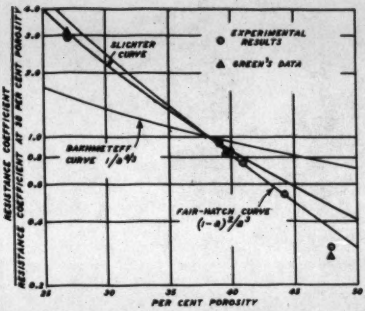


Fig. 4--Relative resistance coefficient versus porosity for aggregations of 0.250-inch diameter steel spheres

Conclusion--The results of these permeability tests indicate that the effect of porosity on resistance coefficient for the case of laminar flow through granular media is expressed best by the Fair-Hatch porosity factor $(1-a)^2/a^3$ when compared with other factors that appear in the literature. This conclusion is based on permeability tests of Ottawa sand, lead shot, and a fine angular sand over the normal porosity range of 34 to 42 pct and on tests of artificial aggregations of uniform spheres at extreme values of porosity. It should be pointed out that granular media of the same grain size with the same porosity may have different resistance to flow because of the different manner in which the void spaces are distributed throughout the media. In general, the resistance to flow of a given medium depends on the direction of flow through the medium. This is particularly true in the case of systematic packings such as cubic loose packing of uniform spheres in which case the resistance to flow in the diagonal direction would undoubtedly be far greater than in the normal direction. For random packing, however, with random orientation of the individual particles, it may be assumed that the voids are evenly distributed and that the resistance to flow is the same in all directions.

Acknowledgment--The material for this paper was derived from a doctoral dissertation. The author is greatly indebted to John K. Vennard, Stanford University, under whose direction the work was done.

References

BAKHMETEFF, B. A., and N. V. FEODOROFF, Flow through granular media, J. Appl. Mech., v. 4A, pp. 97-104, 1937.

BAKHMETEFF, B. A., and N. V. FEODOROFF, Flow through granular media, J. Appl. Mech., v. 5A, pp. 86-90, 1938a.

BAKHMETEFF, B. A., and N. V. FEODOROFF, Flow through granular media, Proc. 5th Internat. Cong. Appl. Mech., pp. 555-560, 1938b.

BAKHMETEFF, B. A., and N. V. FEODOROFF, Discussion of Hatch's paper (see below), Trans. Amer. Geophys. Union, pp. 545-547, 1943.

FAIR, G. M., and L. P. HATCH, Fundamental factors governing the streamline flow of water through sand, J. Amer. Water Works Assn., v. 25, pp. 1551-1563, 1933.

GREEN, LEON, The permeability of a bed of smooth spherical particles, Ph.D. dissertation, Calif. Inst. Tech., 1949.

HATCH, L. P., Flow through granular media, J. Appl. Mech., v. 5A, pp. 85-86, 1938.

HATCH, L. P., Flow through granular media, J. Appl. Mech., v. 7A, pp. 109-112, 1940.

HATCH, L. P., Flow of fluids through granular material: Filtration, expansion and hindered settlement, Trans. Amer. Geophys. Union, pp. 536-545, 1943.

KOZENY, JOSEF, Ueber kapillare Leitung des Wassers in Boden, Sitz. Ber. Weiner Akad. Wissensch., v. 136, pt 2a, p. 271, 1927.

MAVIS, F. T., and E. F. WILSEY, A study of the permeability of sand, Univ. Iowa, Engineering Bull. 7, 1936.

ROSE, H. E., An investigation into the laws of flow of fluids through beds of granular materials, Proc. Inst. Mech. Eng., v. 153, pp. 141-168, 1945.

SLICHTER, CHARLES S., Theoretical investigation of the motion of ground water, 19th An. Rep. of U. S. Geol. Survey, 1897-1898.

Department of Civil Engineering,
Stanford University,
Stanford, California

(Manuscript received August 14, 1950; presented at the Twenty-Sixth Regional Meeting, Fresno, California, February 9, 1951; open for formal discussion until November 1, 1951.)

Transactions, American Geophysical Union Volume 32, Number 3 June 1951

AN IMPROVED SOIL-MOISTURE MEASURING UNIT FOR HYDROLOGIC STUDIES

R. E. Youker and F. R. Dreibelbis

Abstract--A fiberglas gypsum-block soil-moisture unit is described for measuring soil moisture under field conditions from saturation to the wilting point. A sketch of its design and its advantages over other units is presented. The gypsum block serves as a good buffer and contact with the soil, and the fiberglas serves to furnish reliable data in the wet range which the gypsum block alone does not give. It is especially recommended for hydrologic studies where a knowledge of soil-moisture conditions from field capacity to saturation is desirable.

The accurate measurement of soil moisture from the driest point to saturation is essential in soil and water conservation research. In evaluating the hydrologic performance of watersheds, this measurement is useful not only in studies of infiltration and rates of soil-water movement, but is also necessary because of the importance various horizons of the soil profile bear as a medium of water-storage capacity.

During the past decade numerous attempts have been made to devise a reliable method of determining soil moisture. As a result a number of different types of soil-moisture measuring units were placed in use with varying degrees of success. Although the gravimetric method using a soil auger or King tube sampler is still considered by many a reliable method, the chief objection, in addition to its laboriousness, is the destruction of the sampling location to the extent that measurements of soil moisture can never be made more than once in the same place. The electrical resistance method using Bouyoucos gypsum blocks [BOUYOUCOS and MICK, 1940] has proved the most acceptable method where the desired results fall in the range from field capacity to the wilting point. However, hydrologists and other investigators often need to know the moisture content of the soil from saturation to field capacity. A knowledge of the soil-moisture content in these high ranges is essential in studies on infiltration and runoff. For this range the conventional gypsum blocks were found to be unsatisfactory.

COLMAN [and HENDRIX, 1949] has introduced the idea of using fiberglas units which gave him reliable results in the range from saturation to the wilting point. BOUYOUCOS [and MICK, 1948; BOUYOUCOS, 1949] has experimented with a number of new units and recommends both nylon and fiberglas units as acceptable ones for the complete range from saturation to the wilting point. The authors have made preliminary trials with the nylon units and have found them to lack the desired sensitivity for the purposes needed at Coshocton. The Colman fiberglas units have given good results most of the time. On several occasions, however, following prolonged dry periods these units did not respond to increases in soil moisture. Presumably there was an imperfect contact of the units with the soil under such conditions. About three weeks elapsed before they again responded properly to soil-moisture changes. This difficulty was serious enough to make the units undesirable for use at the Coshocton Station.

It appears that in working with soil-moisture measuring units having a small surface area exposed, such as the Colman fiberglas units, there always remains the possibility that an imperfect contact with the soil may result under alternate wetting and drying conditions.

In order to overcome the objections of these various units, the senior author developed a unit at the Coshocton Station that combines the advantages of the gypsum block with that of the fiberglas principle. A sketch of its design appears in Figure 1. In constructing the block the gypsum is poured first into a mold to about half the final depth. Fiberglas cloth 1.25 × 1.25 inches in size is then laid on top of this after which the electrodes are placed with the correct spacing. Another piece of fiberglas cloth is placed over the electrodes after which the remainder of the gypsum is poured to complete the size of the block. The size of the finished block is 2.5 × 1.5 × 0.5 inches; the spacing of the electrodes is 7/8 inch.

The gypsum block serves as a good buffer and contact with the soil, and the fiberglas serves to furnish reliable data in the wet range which the gypsum block alone does not give. It can be used with the same type of bridge as the conventional gypsum blocks. Corrections in resistance readings

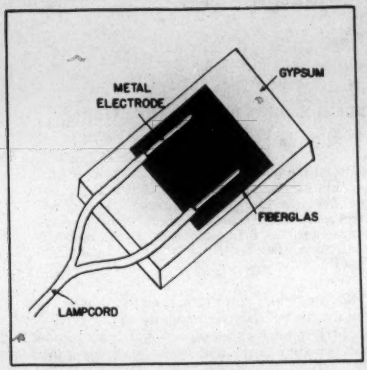


Fig. 1--Cross-section of fiberglas-gypsum block

for temperature changes are the same as those in the gypsum blocks. These fiberglas blocks have been in use by the authors for about two years in connection with studies on infiltration and rates of soil water movement, where a knowledge of soil-moisture conditions prior to and after storm periods is essential. They have been tried under every range of soil-moisture content found under field conditions. They were found sensitive to moisture changes under both wet and dry conditions.

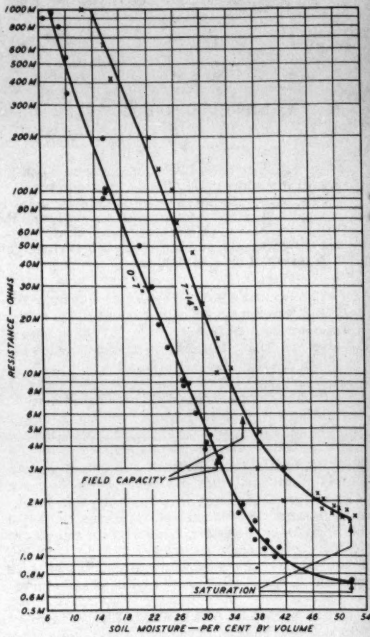


Fig. 2--Calibration curves for Keene silt loam

Calibration curves for the topsoil (0-7″) and subsoil (7-14″) of the Keene silt loam appear in Figure 2. The calibration was made in the laboratory on soil cores of undisturbed structure, three inches in diameter and three inches high. The core was supported in an aluminum tube by a rigid screen covered with cheese cloth to prevent the loss of soil. After saturating by capillarity at which time the weight and resistance reading was taken, progressive drying was carried on and the weight and resistance reading obtained at successive intervals until the soil was air dry. The oven dry weight of soil was used as a basis for computing the percentage of soil moisture. Volume weight data were used to convert to the volume basis which facilitates the conversion of soil moisture to inches water. The calibration curves indicate the reliability of results to be expected in the range between the wilting point and saturation. Soil-moisture fluctuations in the range between field capacity and saturation generally have been difficult to measure accurately. Field calibration curves are often more reliable than laboratory curves. For some of the deeper subsoil layers where parent material fragments are numerous, field calibration curves were found superior to laboratory curves. After using the fiberglas blocks for two seasons, no difficulty was encountered in the response of the fiberglas blocks to increases in soil moisture following prolonged dry periods. The contact between the soil and block remained satisfactory.

The authors present the results of their experience with the fiberglas-gypsum block in the hope it will be of benefit to other investigators desirous of making accurate soil-moisture measurements in situ for the complete range from saturation to the wilting point. It is especially recommended for hydrologic studies where a knowledge of soil-moisture conditions from field capacity to saturation is desirable.

References

BOUYOUCOS, G. J., and A. H. MICK, An electrical resistance method for the continuous measurement of soil moisture under field conditions, Mich. Agr. Exp. Sta. Tech. Bull. 172, 1940.

BOUYOUCOS, G. J., and A. H. MICK, A fabric absorption unit for continuous measurement of soil moisture in the field, Soil Sci., v. 66, pp. 217-232, 1948.

BOUYOUCOS, G. J., Nylon electrical resistance unit for continuous measurement of soil moisture in the field, Soil Sci., v. 67, pp. 319-330, 1949.

COLMAN, E. A., and T. M. HENDRIX, The fiberglas electrical soil-moisture instrument, Soil Sci., v. 67, pp. 425-438, 1949.

Soil Conservation Service,
Coshocton, Ohio

(Communicated manuscript received September 27, 1950;
open for formal discussion until November 1, 1951.)

Transactions, American Geophysical Union Volume 32, Number 3 June 1951

NITRATE IN THE GROUND WATER OF TEXAS

William O. George and Warren W. Hastings

Abstract--Ground water in many parts of Texas contains nitrate in excess of 20 ppm (parts per million) as NO_3. About 3,000 of the 20,000 nitrate determinations made of water from wells in Texas showed more than 20 ppm of nitrate. The public water supplies of 27 Texas towns and cities contained more than 50 ppm of nitrate. Recent medical research indicates that methemoglobinemia or infant cyanosis ("blue babies") may be caused by nitrate in water used in formula mixtures. Most of the high nitrate in ground water is found in wells less than 200 ft deep and mainly in water from late Tertiary and Quaternary formations; however, high nitrate was found in water from all kinds of rocks of all ages. The presence of high nitrate in ground water appears to be unrelated to rainfall, geography, or cultivation.

A hypothesis of bacterial origin of the high nitrate is supported by strong evidence but is weakened by the presence of the correspondingly high content of associated salts. The disappearance of nitrate at depth presents additional problems.

Introduction--Ground water in many parts of Texas has a high nitrate content, as shown by more than 20,000 determinations for nitrate in water samples, most of which were made by the TEXAS BOARD OF WATER ENGINEERS [1948] in cooperation with the U. S. Geological Survey during the last 15 years. Nearly 3,000 of these analyses indicate the presence of nitrate in excess of 20 ppm. All values for nitrate given in this report are expressed as NO_3 unless otherwise noted.

These analyses have been studied and classified with reference to geographic distribution, the geologic age and character of the water-bearing formations, depth of wells, rainfall, and the cultivation of the land. Natural waters do not generally contain more than five to ten ppm of nitrate; therefore, those containing more than 20 ppm are here arbitrarily called "abnormal." Abnormally high nitrate in drinking water has now become a public-health problem, owing to evidence that it is associated with methemoglobinemia or infant cyanosis ("blue babies").

Significance of available data on nitrate--Nitrate probably is more prevalent in water from shallow wells throughout the United States than is generally known. Because its presence or absence has been of little consequence, other than, in some instances, giving some indication of previous contamination by sewage or other organic matter, nitrate generally has been reported only in fairly complete analyses. COLLINS, LAMAR, and LOHR [1934, p. 9] reported: "The effect on industrial use produced by nitrate in water from large industrial supplies is practically negligible. A few waters contain enough nitrate to affect the calculated quantity of sodium or to increase the apparent error in an analysis in which sodium is determined and nitrate not reported."

Recently it has been reported that several parts per million of nitrate in boiler water tends to decrease intercrystalline cracking of boiler steel. In view of the increasing interest in the occurrence of this constituent, chemists are determining nitrate concentrations in nearly all water analyses.

Shallow wells are more likely to yield high-nitrate water than deep wells, but in making ground-water investigations field men are often inclined to select samples for analyses from the deeper, more productive, wells having greater geologic significance, regardless of the relative proportion of deep and shallow wells. In some areas, of course, shallow wells are the principal or only source of potable water, especially for small domestic supplies.

Areas selected for ground-water investigations are generally defined by political boundaries, the county being the most common unit. Such boundaries are not related to geologic or hydrologic units; therefore, it appears that statistical data on the geologic and geographic distribution of nitrates must be used with caution.

Methemoglobinemia--COMLY [1945] advanced the hypothesis that cyanosis ("blue babies") may develop if an infant is fed a formula made with well water having a high content of nitrate

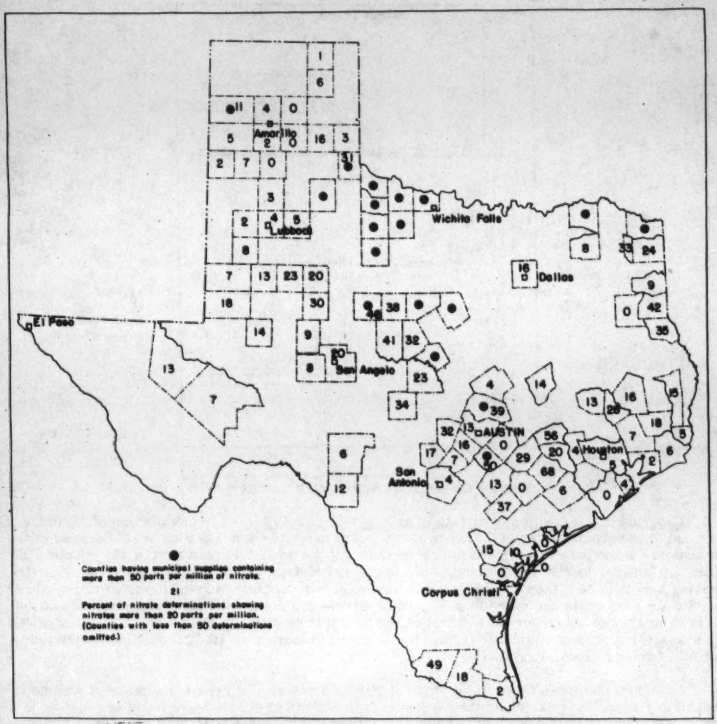


Fig. 1--Distribution of abnormal nitrate in Texas ground water

nitrogen, as follows: "Cyanosis due to methemoglobinemia may occur in infants, with gastro-intestinal disturbances who receive boiled water from poorly constructed dug or drilled farmyard wells with defective casings. The water may contain large amounts of nitrate compounds which when ingested are converted by bacterial action to nitrites. On entrance into the circulation, nitrite oxidizes the ferrous form of hemoglobin to the ferric form with the production of methemoglobin."

In a report published by the National Research Council, MAXCY [1950, p. 265] summarized the observations of a large number of investigators and includes a complete bibliography. He concludes that sufficient observations have been made to establish the validity of Comly's hypothesis; sterilization of water by boiling does not reduce the toxic effects of the nitrates - in fact, the concentration may be increased through evaporation; the danger point of concentration is variously estimated from 20 to 40 ppm, but nitrate nitrogen content in excess of ten ppm (or 44 ppm as NO_3) is regarded as unsafe for infant feeding; and other unknown factors may control the incidence of the disease. Most cases of methemoglobinemia have been reported from the north-central States and from the central provinces of Canada [MEDONY, 1950, p. 228].

The Health Department of the State of Texas has received reports of four cases of methemoglobinemia. Doctors are not required to report the disease to the Health Department and probably not all known cases have been reported; other cases may not have been recognized.

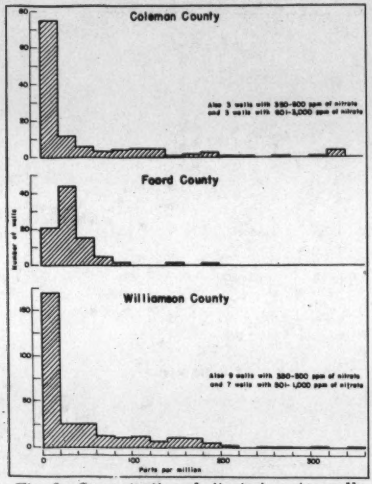


Fig. 2--Concentration of nitrate in water wells

Geographic distribution of nitrate in ground water in Texas--The distribution of abnormal nitrate in the ground water of Texas is shown, from available data, on Figure 1. Because of the magnitude of the data it is not feasible to present all the analytical data for the 254 counties of Texas. In order to give more significance to the percentage values shown on the map, counties having less than 50 nitrate determinations were omitted. Counties having towns or cities whose public supplies contained more than 50 ppm of nitrate are designated separately because of the larger number of users per well. Most of the 27 towns or cities in the counties thus designated are small, but populations range from a few hundred to more than 10,000. In some of the towns no other source of water is available.

Abnormal nitrate is found in all parts of Texas; however, the greatest number of samples containing abnormal nitrate and the highest concentrations of nitrate were found in counties of central Texas. In Coleman County, 58 of 133 waters had a nitrate content of more than 20 ppm; three samples contained respectively 1440, 1610, and 1950 ppm. Wells yielding water containing more than 500 ppm of nitrate were found in Blanco, Hays, Childress, Cass, Travis, Williamson, Coleman, and Mason Counties. In Williamson County, 246 of 625 well waters were abnormal, whereas in Galveston County only 43 of 1151 waters were found to be abnormal. In Figure 2, wells yielding abnormal-nitrate waters in Coleman, Foard, and Williamson Counties are classified according to the concentration of nitrate.

Relation of abnormal nitrate to rainfall--Nitrate salts, because of their high solubility in water, are less likely to be found in the rocks and soils of humid regions than in those of arid regions. The distribution of abnormal nitrate in the ground water in Texas, however, appears to have little relation to present climatic conditions.

The average rainfall in Texas ranges from about ten inches per year in the western part to more than 50 inches per year in the extreme eastern part of the State. In western Texas less than ten per cent of the samples of water from wells contained abnormal nitrate.

In central Texas, where the average rainfall ranges from 20 to 30 inches a year, high concentrations of nitrate in well water are more prevalent. In eight counties in north-central Texas, where the average rainfall is about 25 inches a year, 40 pct of the 327 wells sampled showed abnormally high nitrate. In Williamson County, in south-central Texas, where the average annual rainfall is more than 30 inches, nearly 40 pct of the wells yield water having a nitrate content of more than 20 ppm. In eastern Texas, where the average annual rainfall is more than 50 inches,

abnormally high nitrates in well waters are not unusual. In Shelby County, where the normal annual rainfall is about 45 inches, 35 pct of the 159 wells sampled had a nitrate content greater than 20 ppm.

Relation of abnormal nitrate to cultivation and pollution.--The possibility of infiltration of nitrate from dissolved commercial fertilizers to the water table has been considered. Inquiry among farmers in the vicinity of Crowell, Foard County, where the amount of nitrate in ground water is abnormal, revealed that no fertilizers of any kind had been used on the land.

Approximately one-fifth of the total area of Texas was in cultivation in 1945. A study of the distribution of abnormal nitrate as related to cropland shows that, in one group of 14 counties where 24 pct of the land was in cultivation, abnormal nitrate was found in 30 pct of the wells sampled. In another group of 14 counties where 21 pct of the land was cultivated, abnormal nitrate was found in less than 20 pct of the wells.

It has been fairly well established that, although pollution may increase the nitrate content of water, abnormal nitrate does not necessarily indicate pollution [CLARKE, 1924, p. 197]. Through the courtesy of C. H. Billings, Assistant Chief Engineer, Texas State Health Department, a number of sanitary analyses of municipal supplies obtaining water from the Seymour formation (Fig. 3) of Pleistocene age were studied. These municipal wells are less than 60 ft deep and all yield water containing abnormal nitrate. These sanitary analyses show no more pollution than might be expected in view of the difficulties of controlling sanitation around shallow wells; the pollution definitely is not sufficient to account for the high concentration of nitrate found in the water. Some well waters, known to be polluted, have been analyzed by the U. S. Geological Survey and have shown only two or three ppm of nitrate; some others have contained as much as 600 ppm. On the basis of all the nitrate data for Texas ground water, undoubtedly some high nitrate is the result of pollution, but the association of pollution with all wells yielding waters abnormally high in nitrate is beyond reasonable probability.

Relation of abnormal nitrate to depth and geology--Probably more than 95 pct of the wells yielding abnormal-nitrate waters are less than 200 ft deep. None of the few wells of greater depth that yield water high in nitrate can be positively classified as such, because in many of them the water may enter the well from various depths above the bottom. In wells having the upper strata sealed off by casing there is always the possibility of a leak in the casing.

In Texas, abnormal nitrate is found in water from formations of all geologic ages; in marine and non-marine formations; and in limestone, sandstone, sand, gravel, and tuff. Nitrate is generally more prevalent in water from wells in the outcrop of the formations than down dip under cover of younger formations. The formations that yield water high in nitrate do not necessarily contain large amounts of organic material.

Information as to the geologic age of the source bed is not available for all the water samples analyzed; however, more than half the samples showing abnormal nitrate were obtained from late Tertiary and Quaternary formations. In general, these formations dip at low angles and have wide outcrops in which a large number of shallow wells yield water containing abnormal nitrate. An exception is the low nitrate in ground water from the Ogallala formation (Pliocene), which yields large quantities of water to wells in the High Plains. The Ogallala lies unconformably on older rocks and yields water under water-table conditions to wells that average more than 200 ft in depth. Abnormal nitrate, where present, is generally found in the comparatively shallow wells less than 100 ft deep.

The greater part of Texas is drained by mature streams that have deposited alluvial material since early Pleistocene time. The deposits consist chiefly of sand and gravel and are rarely more than 50 ft thick. Wells drilled or dug in these deposits generally yield water high in nitrate. Analyses of water from wells in the counties in which Pleistocene river deposits are widespread are likely to show abnormal nitrate.

In north-central Texas (see Fig. 3) a large area is covered by remnants of the Seymour formation, consisting of stream-deposited sand and clay of Pleistocene age. The average thickness of the formation is about 50 ft. The Seymour formation is the only source of potable ground water in the area, and nearly all the water from wells in this formation has abnormal nitrate.

In some parts of southeastern Texas, the water-bearing sands in formation of Tertiary and Quaternary age are likely to yield abnormal-nitrate waters to shallow wells in the outcrops. Analyses of water from the same formations obtained down dip at greater depth, however, rarely show more than three ppm of nitrate.

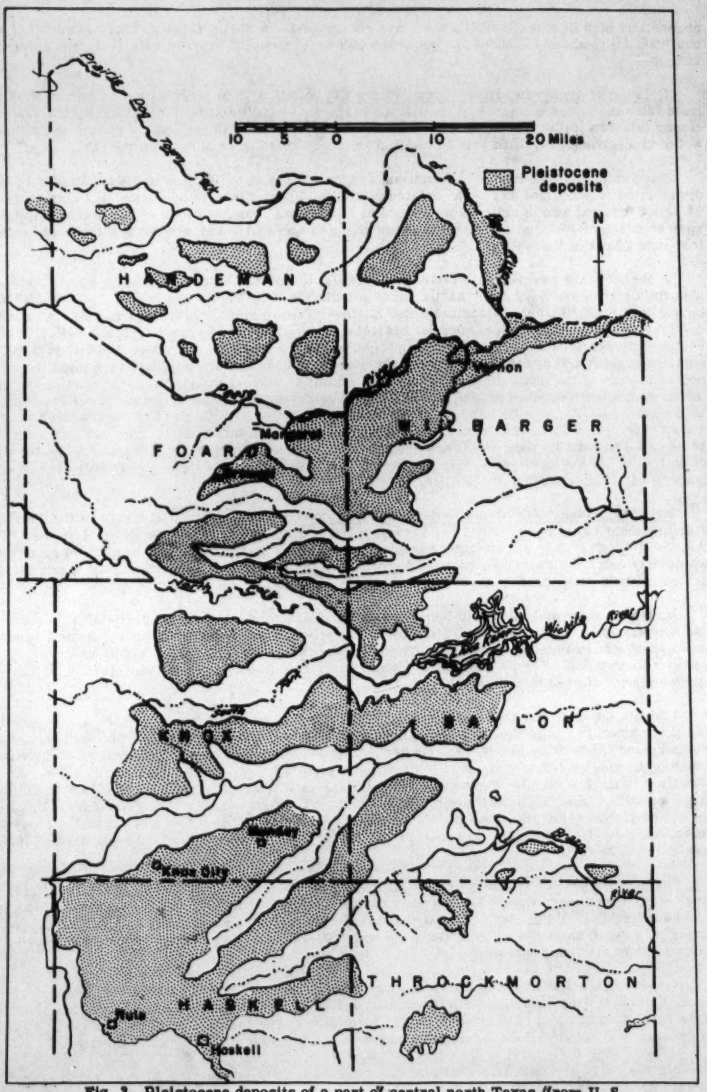


Fig. 3--Pleistocene deposits of a part of central north Texas (from U. S. Geological Survey, Geologic Map of Texas)

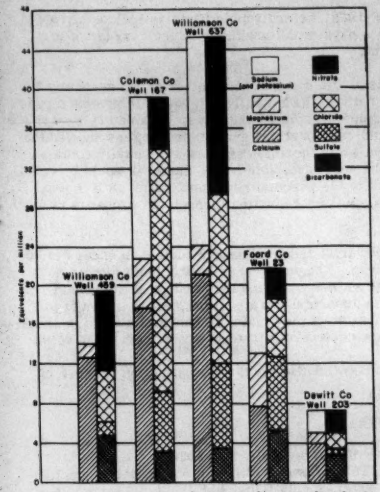


Fig. 4--Analyses of waters from individual wells in counties where high concentrations of nitrate are common

Chemical character of high-nitrate ground waters--Analyses of high-nitrate ground water in wide ranges of concentration are shown graphically in Figure 4. Many of the waters containing abnormal amounts of nitrate are highly mineralized. Nitrate is not the predominant anion in most waters, even in those of very high nitrate concentration. Waters containing as much as 500 ppm, or even more, of nitrate generally contain correspondingly greater amounts of chloride and sulfate. High-nitrate water is generally characterized by a high calcium content and a comparatively low magnesium content. Sodium is present in many waters in about the same quantity as calcium. Waters of lower mineral content, where the nitrate concentration ranges from 20 to 40 ppm, are typically calcium-carbonate waters having sulfate and chloride in about the same amounts as nitrate.

Origin of nitrate--In contrast to the large percentage of nitrogen in the atmosphere, the amount of combined nitrogen in the rocks and minerals in the Earth is small, according to CLARKE [1924]. Concentrations of nitrate-bearing rocks are found in arid regions, but even after extensive studies by GALE [1919], NOBLE [1931], MANSFIELD and BOARDMAN [1932], and many others the origin of these nitrate deposits is still somewhat in doubt. Rivers and lakes are not seriously polluted, and sea water generally contains less than three ppm of nitrate.

The mineral content of ground water comes almost entirely from the soils and rocks through which the water percolates. Nitrate minerals in primary or volcanic rocks from which sedimentary rocks are derived are rare or sparsely disseminated. There are, moreover, no known concentrations of nitrate minerals in the water-bearing formations in Texas.

The formation of ammonia by lightning during thunderstorms has been considered as a possible source of nitrate. The volume of nitrate from the atmosphere is probably too small to account for the amount of nitrate in ground water [CLARKE, 1924].

There appears to be some evidence to support a bacterial origin for abnormal nitrate in water. THIEL [1927] demonstrated in the laboratory the effectiveness of bacteria as agents of denudation. According to WAKSMAN [1932], soils are abundantly supplied with nitrate-forming (autotrophic) bacteria that can obtain energy from inorganic compounds in the presence of oxygen. Leguminous plants also assist in fixing nitrates in the soil. The hypothesis is weakened, however, by the fact that water containing high concentrations of nitrate generally contains correspondingly large amounts of chloride and sulfate.

The fact that abnormal-nitrate water is found in nearly all the Pleistocene fluvial deposits, particularly the Seymour formation (see Fig. 2), overlying the Permian rocks of north-central Texas, suggests that nitrate-bearing saline residues of the Permian might have been carried in by the rivers that deposited the Pleistocene sediments. In general, however, these deposits are favorably situated for natural discharge as well as recharge by meteoric water, and it is reasonable to suppose that all or nearly all the original water has been replaced by meteoric water since Pleistocene time.

In the large ground-water reservoirs near the Gulf Coast, ranging in age from Miocene to Recent, shallow wells are likely to yield high-nitrate waters. However, these waters move down dip toward the Gulf Coast to supply the deeper artesian reservoirs. As the wells become deeper the concentrations of nitrate are generally smaller, and few, if any, deep wells in the Gulf Coast area yield abnormal-nitrate water. What becomes of the nitrate? One can hardly assume that the formation of nitrate is a recently acquired trick of nature or that not enough time has elapsed for water in the outcrop to move down to depths of several hundreds of feet. It must necessarily be assumed that something happens to the nitrate in transit.

According to the classification of WAKSMAN [1932], heterotrophic bacteria include nitrate-reducing bacteria that thrive in the absence of free oxygen and use the combined oxygen of nitrates, provided that a source of energy is present.

It is well known that ground water in the Coastal Plain and in some other areas generally becomes softer at depth because of the exchange of cations [RENICK, 1924], but little has been published on the changes that take place in the anions under natural conditions. Laboratory experiments by SPIEGLER and HELLINGER [1950, p. 409] with bacteria and ion exchangers showed that "The cation-exchange effluent was free of bacteria while the anion effluent was heavily contaminated." With ferrous iron and nitrate-reducing bacteria available in the Earth, it would be reasonable to expect a reduction in the nitrate content of the percolating ground water as it moves from the shallow sands to the artesian reservoirs. Nitrate reduction through ion exchange is a possibility.

Conclusions--Abnormal nitrate in Texas (arbitrarily assumed as any content in excess of 20 ppm) is generally found in wells less than 200 ft deep. The occurrence of abnormal nitrate does not appear to be related to rainfall, geography, cultivation, or to the kind or age of the reservoir rocks. Pollution is not necessarily associated with abnormal nitrate. Conclusions drawn from the data studied do not lead to a satisfactory explanation of the origin of abnormal nitrate in shallow ground water, or to the generally comparatively low content of nitrate in water from deep wells.

Acknowledgment--The writers are grateful to D. M. Suttle for the classification of much of the data contained in this paper.

References

CLARKE, F. W., The data of geochemistry, U. S. Geol. Survey Bull. 770, 1924.

COLLINS, W. D., W. L. LAMAR, and E. W. LOHR, The industrial utility of public water supplies in the United States, 1932, U. S. Geol. Survey Water-Supply Paper 658, 1934.

COMLY, H. H., Cyanosis from nitrates in well water, Amer. Med. Assn. J., v. 129, pp. 112-116, 1945.

GALE, H. S., Our mineral supplies, U. S. Geol. Survey Bull. 666-Z, 1919.

MANSFIELD, G. R., and LEONA BOARDMAN, Nitrate deposits of the United States, U. S. Geol. Survey Bull. 838, 1932.

MAXCY, KENNETH F., Report on the relation of nitrate nitrogen concentrations in well waters to the occurrence of methemoglobinemia in infants, Nat. Res. Coun., Bull. Sanitary Eng. and Envir., App. D, 1950.

MEDONY, HARRY, Methemoglobinemia, Canadian Med. Assn. J., v. 562, 1950.

NOBLE, L. F., Nitrate deposits in southeastern California, U. S. Geol. Survey Bull. 820, 1931.

RENICK, B. COLEMAN, Base exchange in ground-water by silicates as illustrated in Montana, U. S. Geol. Survey Water-Supply Paper 520, pp. 15-26, 1924.

SPIEGLER, K. S., and ESTER HELLINGER, Effects of partial demineralization of water on bacteria, Amer. Water Works Assn. J., v. 42, 1950.

TEXAS BOARD OF WATER ENGINEERS, Progress report, 1946-48 (contains list of publications on ground water in Texas, most of which contain water analyses including nitrate determinations), 1948.

THIEL, GEORGE A., The relative effectiveness of bacteria as agents of chemical denudation, J. Geology, v. 35, pp. 647-652, 1927.

WAKSMAN, SELMAN A., Principles of soil microbiology, Williams and Wilkins Co., Baltimore, Md., 1932.

U. S. Geological Survey (W.O.G.),
Austin, Texas

U. S. Geological Survey (W.W.H.),
Washington, D. C.

(Communicated manuscript received December 19, 1950;
open for formal discussion until November 1, 1951.)

Transactions, American Geophysical Union Volume 32, Number 3 June 1951

THE STRUCTURE OF THE BED OF THE ATLANTIC OCEAN

J. P. Rothé

Abstract--The working hypothesis which the author developed in 1947 is summarized: The Atlantic Ocean is divided into two zones, an occidental zone where the bed is constituted of simatic rocks and, in contrast, to the east of the Mid-Atlantic Ridge, a zone of continental structure.

A study is made of the distribution of epicenters, the forms of the coasts, the extension of the morphological unities of the African Continent under the oriental part of the Atlantic Ocean, and the high velocity of Love waves under the occidental part. The work of P. Caloi and others is discussed, and new arguments are brought forward in favor of the author's hypothesis: dredging of tachylyte by Termier, of Trilobites by Furon, of cenozoic limestone by Ewing and Tolstoy in the oriental part; theory of sialo-simatic thermodynamic cycles by Glangeaud; results of refraction seismic measurements obtained at the west of Scotland by Hill and near the Bermudas by Ewing.

The structure of the bed of the Atlantic Ocean has attracted the attention of many workers. Three of our Italian colleagues, CALOI, MARCELLI, and PANNOCHIA [1949, 1950] have recently published two papers concerning my "working hypothesis" presented to the Congrès des Sociétés Savantes Françaises in Strasbourg, April 1947 [ROTHÉ, 1947a and b]. I want now to bring forward this question again, and to discuss the results obtained by my Italian colleagues as well as the new arguments drawn from recent works.

As is known, Wegener took the idea of his continental-drift theory from the similar forms of the American and African Atlantic Coasts. However, several seismological and morphological facts have led me to the following "working hypothesis": The Atlantic is divided into two zones. To the east of the Atlantic Ridge is a zone of continental structure connected to the African block, and, in contrast, the western part of the Atlantic is probably of Pacific structure (only simatic rocks).

Fig. 1--The structure of the Atlantic Ocean [ROTHÉ, 1947a]; points 1 to 5 show the position of dredging or of seismic refraction stations

In this way, the parallelism noticed by Wegener, du Toit, and others between the outlines of the African and American Coasts is to be looked for between the American Coast and the Mid-Atlantic Ridge, the general forms being the same (see Fig. 1). If there has been a drift, it is only over the distance from the Mid-Atlantic Ridge to the American Coast. The real Atlantic Ocean (sensu stricto) is the wide gap open to the west of the Mid-Atlantic Ridge between the continental Euro-African and American blocks. The more and more probable existence of Atlantis, that is, a collapsed mass between the Azores and Morocco, is a strong objection to the continental-drift theory. My hypothesis eliminates this and explains also that the average earthquake wave velocity under the Atlantic (as a whole) is intermediate between the velocities under the Pacific and under the continents.

The seismological and morphological facts which have attracted my attention may be summarized as follows:

(1) We know the seismicity of the Earth well. Many determinations of epicenters are available (including International Seismological Summary, Bureau International de Séismologie de Strasbourg, and the extensive works by GUTENBERG and RICHTER [1949]). The distribution of these epicenters is striking. There are some large stable

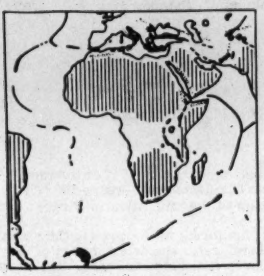


Fig. 2--African stable mass surrounded by seismic active belts [GUTENBERG and RICHTER, 1949]

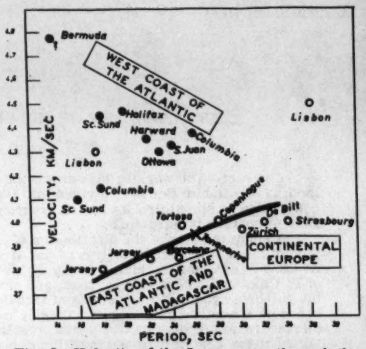


Fig. 3--Velocity of the Love waves through the Atlantic Ocean (after CALOI [1949], interpreted by Rothé)

blocks bounded by narrow seismic belts; among them there is an African block much larger than the actual continent of Africa (Africa such as it is shown on the accompanying geographical map, see Fig. 2). To the west this block is limited by the mid-Atlantic seismic belt, to the north by the Alpine seismic belt which follows the Alpine folding (Himalaya, Caucasus, Carpathians, Alps, Apennines, Atlas, Cordillera Betica) and joins the mid-Atlantic seismic belt near the Azores. It joins this belt but does not pass through it. Contrary to what was thought, there is no sign of seismicity between the Mid-Atlantic Ridge and the West Indies. Thus the distribution of epicenters shows that the "géosynclinal de la Mésogée" does not pass through the Atlantic from one end to the other and does not join the Pacific geosynclinal.

(2) LYNCH [1945] calculated the velocity of Love waves for the earthquake of September 14, 1945, which occurred on the Mid-Atlantic Ridge (epicenter 7.0°N, 38.8°W). According to the data registered at Fordham he finds a speed of 4.4 km/sec for a wave period of 23 sec. This figure is slightly higher than the one found for Love waves under the Pacific.

(3) My colleague, G. Dubois, Professor of Geology at the University of Strasbourg, with whom I have often discussed the fascinating problem of the structure of the Earth, has pointed out the interest of the new bathymetrical measurements effected in the Atlantic Ocean. These measurements show that in the South Atlantic at the east of the Mid-Atlantic Ridge many alternative basins and ridges with a SW-NE trend continue the morphological units of the African continent. These units are indicated in Figure 1 according to the map published by UMBGROVE [1947].

(4) We know that the eastern shoreline of the United States and of the Maritime Provinces of Canada shows a morphological character of the Pacific type (the relief extends in directions parallel to the coast); in contrast, the coasts of Spain and Brittany are "rias" coasts (Atlantic type).

(5) The loops of the West Indies (including Puerto Rico, Martinique, Guadeloupe) and of the South Antilles (including South Georgia, Sandwich, South Orkneys) occupy the same position (see Fig. 1) with respect to the western margin of the Atlantic Ocean as the island arcs (Kuriles, Mariannes, and others) with respect to the western edge of the Pacific Ocean.

With regard to the paper by CALOI, MARCELLI, and PANNOCHIA [1949] who report on the velocities of Love waves of an earthquake originating in the Mid-Atlantic Ridge (8° 02'N, 38° 24'W), the following points are cited:

(1) Figure 8 of their paper (see Fig. 3 of this paper) shows clearly the distribution of the seismographic stations in two groups, namely, (a) the American stations near the Atlantic Coast (San Juan, Bermuda, Halifax, Harvard, Ottawa) (the calculated velocities are very high); (b) the European stations and also the station of Tananarive (the velocities are much lower; there is only one anomaly, the high velocity found at Lisbon).

(2) The difference between the velocities under the western part and under the eastern part of the Atlantic is remarkable, especially as the waves must pass through a continental shelf (submerged "Appalachia") from 200 to 300 km wide in addition [EWING, WOOLLARD, and VINE, 1939] to reach the American stations. One can compare the respective lengths of the continental and oceanic paths from the epicenter to Ottawa, Jersey, Tortosa, and Barcelona as shown in

Table 1--Lengths of continental and oceanic paths from mid-Atlantic epicenter

Station	Oceanic path	Continental path	Total path
	km	km	km
Ottawa	4600	800	5400
Jersey	5300	400	5700
Tortosa	4300	1000	5300
Barcelona	4500	1000	5500

Table 1. Although the total paths to all four stations are of the same order of length, nevertheless the average velocity calculated at Ottawa is 0.4 km/sec higher than the one at the three European stations.

(3) Concerning the Tananarive station, the Italian workers write: "Nel quadrante sud orientale le osservazioni sismiche sono limitate a quelle della stazione di Tananarive. La relativamente elevata velocita di propagazione osservata per le onde superficiali registrate in detta stazione lasciano pero ritenere che il tragitto atlantico di dette onde ha interessato zone ad elevatissima velocita per le onde superficiali."

Figure 3, however, shows clearly that the graph of the velocity at Tananarive (4.0 km/sec) falls on the curve passing through the points representing the velocities calculated at the stations located east of the Mid-Atlantic Ridge. I think that this fact corroborates the homogeneous structure east of the Mid-Atlantic Ridge, whether the path shown on the map is oceanic or continental.

(4) The epicenter map [CALOI, MARCELLI, and PANNOCHIA, 1949, Fig. 11], showing as it does all epicenters determined by the International Seismological Summary, no matter how small the earthquake, gives a misleading picture because of the large density of the European seismological stations. GUTENBERG and RICHTER [1948; 1949, p. 71; 1950] confirm their earlier opinion in their recent extensive work: "Seismic data support a continuation of the active belt into the Atlantic as far as the Azores but not farther. There is no justification for extending it to the West Indies, as was done on some early seismic maps of the world."

In this seismic belt are in particular the foci of the tremendous earthquake of 1755 (so-called "Lisbon Earthquake," probable magnitude 9) and the earthquake of November 25, 1941 (magnitude 8.3) responsible for the breaking of the Brest-Casablanca and Brest-Dakar submarine cables.

According to the work of the American authors, epicenters between 10° and 32° are as shown in Table 2. This list is not exhaustive. It comprises only a certain number of shocks chosen "because their epicenters contribute to seismogeographic information." The fact that this active belt does not pass through the western part of the Atlantic has always seemed very important to me.

Table 2--Epicenters between 10° and 32°W

Date	North latitude	West longitude	Magnitude or class
	°	°	
Dec. 27, 1941	36	10.5	6 3/4
July 11, 1915	37	10.5	6 1/4
Mar. 7, 1930	32	11.5	d
May 20, 1931	37.5	16	7.1
Nov. 25, 1941	37.5	18.5	8.3
May 29, 1942	38	19	d
Oct. 21, 1930	36.5	23	d
May 8, 1939	37	24.5	7.1
Aug. 15, 1933	38	26.5	d
Aug. 31, 1926	38.5	28	d
Apr. 5, 1926	39	29	6
July 9, 1931	40.2	29.5	d
July 18, 1923	42	29.5	d
July 9, 1926	38	30	d
Aug. 27, 1924	41.5	30.5	d
July 29, 1941	38.5	32	d

(5) There are, of course, to the east of the Mid-Atlantic Ridge, deep marine basins. However, there are also ridges which extend to the structural lines of Africa. It must be remembered that a folded chain (like the Alpine chain) extends to 50-60 km in depth. This depth is ten times that of these marine basins. The geological phenomena which play an important part in the division of the Atlantic into two parts extend certainly to the whole crust. In any case, the detailed work of our Italian colleagues confirms the earlier isolated data: The velocity of Love waves under the western Atlantic is very high and therefore the bottom is probably formed of simatic rocks.

I would like to summarize a few works, some of them recent, and some that I have read since my initial paper.

(1) The eminent French geologist GLANGEAUD [1947b] has published an interesting paper explaining the "orogénèse" (folding of mountains) by sialo-simatic thermodynamic cycles. He writes in particular: "Dans toutes les chaines qui se forment ainsi au contact du bloc sialique continental et du sima sous-océanique on peut admettre un rôle plus ou moins accentué de la palingénèse crustale. Notre hypothèse explique pourquoi de telles chaines liminaires, de direction méridienne, jalonnent la bordure du Pacifique en Amérique comme en Asie. Elles paraissent

partout où les masses sialiques continentales s'affrontent avec le sima qui occupe une partie du fond du Pacifique. Les phénomènes des chaines liminaires doivent ainsi continuer de nos jours, à la limite du sial et du sima, au Japon, en Californie, sur la bordure orientale des Antilles, et le long de la crête atlantique.

"Or J. P. Rothé a émis l'hypothèse que la crête atlantique est située à la limite du bloc sialique africain et du fond simique de l'ouest-Atlantique. Elle serait ainsi placée dans les conditions de formation des chaines liminaires sialo-simiques."

It can be seen that my hypothesis likewise entails a general explanation of the formation of the Mid-Atlantic Ridge, an important structural element, mysteriously located.

Folding and uplifts of viscous basaltic magma injected through the granitic zone and through sedimentary layers might very likely take place along the Mid-Atlantic Ridge. These phenomena are similar to those described and explained by GLANGEAUD [1946, 1947b]: The "Atlas Tellien" (French North Africa) forms the boundary chain between the African continental block and the "Mésogée." The central basin of the western Mediterranean, inactive from the seismic point of view, seems like a lake or rather a hole filled with simatic material in the middle of the sialic Euro-asiatic and African blocks.

(2) The data on the geological nature of the Atlantic sea bottom are very scanty. Nevertheless, several papers are cited. TERMIER [1924] pointed out a discovery made in 1898 by a cable ship. At 47° 00′N, 27° 20′W, and at a depth of 3100 m, a specimen of lava, so-called tachylyte, was found. Termier thought that this lava formed itself under atmospheric pressure and that therefore "la terre qui constitue aujourd'hui le fond de l'Atlantique à 900 km au nord des Açores a été recouverte de laves quand elle était encore émergée." This place corresponds to a point of the active belt of the Mid-Atlantic Ridge, the boundary between the simatic block and the sialic zones (Fig. 1, point 1). Termier wrote that very few geologists understood the great importance of the discovery. The specimen found is now incorporated into the geological collection of the "Ecole des Mines de Paris."

(3) The new methods of dredging used by the Swedish and American hydrographic expeditions are very promising. TOLSTOY and EWING [1949] reported that specimens of Cenozoic limestones have been found at two points (Fig. 1, points 2 and 3) near the Mid-Atlantic Ridge. They conclude: "One of the big surprises of the 1947 Atlantis expedition (cruise 150) was the proof of the existence of consolidated Cenozoic limestone on the Mid-Atlantic Ridge. Possibly considerable areas of the Ridge consist of sedimentary rocks. If so, the hypothesis of folded ranges in certain parts of the Ridge should not be rejected arbitrarily on the sole basis that it is difficult in the light of our scanty knowledge of the history of the Earth's crust to explain the why and how of such a process. It must be disproved by experimental and observational data; until then it remains a possibility."

(4) The seismic refraction method is now used up to 2800 fm of water and allows an investigation of the ocean floor. In August 1949 the Department of Geodesy and Geophysics of the University of Cambridge (England) operated at 53° 50′N, 18° 40′W (under 1300 fm) (Fig. 1, point 4). HILL and SHALLOW [1950] summarize the results as follows: "The low values for the velocity in the surface layer (from about 5000 ft/sec at the surface of the sea bed to a maximum value of approximately 8000 ft/sec) indicate not highly consolidated marine sediments .... The velocity in the layer below the sediments is igneous rocks such as granite (16,300 and 17,300 ft/sec). The depth below sea level of this layer is approximately the same as that of the continental granitic layer, but its thickness, 8800 ft, is considerably less.

"The two observations (21,700 ft/sec and 20,600 ft/sec of the velocity in the third type of rock are close to the value assigned to the intermediate layer lying between the granitic and ultrabasic layers as determined from near earthquakes."

Finally, a reversed seismic refraction measurement was made in 2800 fm of water at latitude 34°N, longitude 66° 30′W (120 mi northwest of Bermuda and 400 mi off Cape Hatteras, Fig. 1, point 5).

EWING and others [1949] wrote: "The ocean floor was found to be composed of two layers. A velocity of 24,000 ft/sec (7.58 km/sec) was found for the second layer. This was identified with the Pn waves of earthquake seismology attributed to the basaltic layer found below the Mohorovicic discontinuity. A first layer was clearly present, but the velocity was not determined. A velocity of 5600 ft/sec (1.70 km/sec) was assumed, giving a thickness of 4500 ft for this sedimentary layer. This velocity was chosen from some of our earlier measurements, as yet mostly unpublished. The granitic and intermediate layers are thus absent beneath the ocean floor at this point. The velocity of the basaltic layer compares favorably with those of Slichter in New England and with Jeffreys' world average."

Bucher [LEET, 1950], at the November 1949 meeting of the Geological Society of America in El Paso, Texas, stated: "Ewing's conclusions cast doubt on the belief that the floor of the Atlantic is underlain by a thin granitic shell. Granitic material may be absent over large parts of all oceans."

To conclude, it is sufficient to examine on the map (Fig. 1) the position of the points 1 to 5. The nature of the sea bottom is really the one foreseen according to my hypothesis as shown in Table 3.

Table 3--Nature of the sea bottom

Point	Zone	Rock type
1	Sialic Atlantic	Submerged lava
2	Sialic Atlantic	Cenozoic limestone
3	Sialic Atlantic	Cenozoic limestone
4	Sialic Atlantic	Sediments over granite or paleozoic rocks
5	Simatic Atlantic	No granite

In a short note L. Don Leet mentions "in contrast" the measurements (related above) made by the English and the American geophysicists. My conception of the Atlantic structure explains immediately this contrast. The Mid-Atlantic Ridge is the boundary chain of the sialic African block and separates the two parts of the ocean into two dissimilar structures. The seismicity shows that the orogenic phase is still active along the Mid-Atlantic Ridge.

References

CALOI, P., L. MARCELLI, and G. PANNOCHIA, Sulla velocita di propagazione delle onde superficiali in corrispondenza dell'Atlantico, An. Geofisica, v. 2, pp. 347-358, 1949.

CALOI, P., L. MARCELLI, and G. PANNOCHIA, Ancora sulla velocita di propagazione delle onde superficiali per tragitti subatlantici; Tentativo di prospezione profonda del bacino Atlantico mediante le curve di dispersione delle onde L_q, An. Geofisica, v. 3, pp. 215-222, 1950.

EWING, M., G. P. WOOLLARD, and A. C. VINE, Geophysical investigations in the emerged and submerged Atlantic Coastal Plain, pt. 3, Bull. Geol. Soc. Amer., v. 50, pp. 257-296, 1939.

EWING, M., and others, Short notes, Bull. Geol. Soc. Amer., v. 60, pp. 1303-1304, 1949.

GLANGEAUD, L., Étude thermodynamique de la Pétrogénèse profonde, Bull. Soc. Géol. France, 5 ser., v. 16, pp. 563-584, 12 fig., 1946.

GLANGEAUD, L., Orogénèse et Pétrogénèse profonde, d'après les théories géophysiques nouvelles, Revue Scientifique, v. 85, pp. 1107-1120, 13 fig., 1947a.

GLANGEAUD, L., Les états de la matière dans la pétrogénèse profonde, Experientia, v. 3, pp. 11-26, 58-70, 27 fig. 1947b.

GUTENBERG, B., and C. F. RICHTER, Erdbeben Geographie und Dynamik der Erdkruste, Die Naturwissenschaften, v. 35, no. 7, pp. 196-202, 1948.

GUTENBERG, B., and C. F. RICHTER, Seismicity of the Earth and associated phenomena, Princeton Univ. Press, 1949.

GUTENBERG, B., and C. F. RICHTER, Géographie dès tremblements de terre et dynamique de la croûte terrestre, An. Inst. Phys. Globe, Strasbourg, pt. 3, Geophys., v. 5, pp. 3-11, 1950.

HILL, M. N., and J. C. SHALLOW, Seismic experiments in the Atlantic, Nature, London, v. 165, pp. 193-194, 1950.

LEET, L. DON, Atlantic basement rocks, Bull. Geol. Soc. Amer., v. 61, p. 411, 1950.

LYNCH, W. A., Surface-wave velocities over the Atlantic, Earthquake Notes, v. 17, p. 8, 1945.

ROTHÉ, J. P., Hypothèse sur la formation de l'Océan Atlantique, C.-R. Acad. Sci., Paris, v. 224, pp. 1295-1297, 1947a.

ROTHÉ, J. P., Quelques aspects de la structure terrestre éclairés par la sismologie, Revue Scientifique, v. 85, no. 3271, pp. 401-408, 1947b.

TERMIER, P., A la gloire de la Terre, 2nd ed., Paris, 1924, pp. 117-146.

TOLSTOY, I., and M. EWING, North Atlantic hydrography and the Mid-Atlantic Ridge, Bull. Geol. Soc. Amer., v. 60, pp. 1527-1540, 1949.

UMBGROVE, J. H. F., The pulse of the Earth, 2nd ed., The Hague, 1947.

Faculté des Sciences de Strasbourg,
Strasbourg, France

(Communicated manuscript received October 30, 1950;
open for formal discussion until November 1, 1951.)

Transactions, American Geophysical Union Volume 32, Number 3 June 1951

AN EXAMPLE OF RE-INTRUSION OF SERPENTINE

Robert G. Thomas

Abstract--An area in the central coast ranges of California near Redwood City has been mapped and evidence is submitted for re-intrusion of a serpentine mass in a cold state. The re-intrusion is believed to have occurred during the period between upper Eocene and lower Miocene. Original emplacement of the ultra basic magma occurred during late upper Jurassic times. The significance of this study is that serpentine bodies may be moved considerable distances by pressures developed during orogenies subsequent to the time of original intrusion.

Introduction--The occurrence of serpentine masses has been studied in California, but little has been written on the effect of orogenies on these masses. An example of re-intrusion of serpentine has been mapped by the author during 1949 while mapping a larger region. The area to be discussed is located in the foothills of the Santa Cruz Range two miles southwest of Redwood City, California, in portions of the Half Moon Bay and Palo Alto quadrangles. The region was mapped by BRANNER [1909] but no literature subsequent to that could be found.

Description of the formations--The geologic map (see Fig. 1) shows the distribution of the formations involved in this discussion. They are serpentine, an unnamed formation of Eocene or Paleocene age and rocks of the Franciscan formation of Jurassic age. The unnamed Eocene or Paleocene formation was called "Chico" by Branner on a lithologic basis and was assigned to Upper Cretaceous. Collections of Foraminifera by MARTIN [1937] and the author have indicated that the formation is of Eocene or Paleocene age. From 4000 to 6000 ft of the Eocene formation is exposed in the map area. The formation consists of alternating marine sandstone, clay, and shale beds from a fraction of an inch to 200 ft thick.

The Franciscan formation consists of sandstone, shale, chert, and slightly altered igneous rocks including basalt, basaltic tuff, and diabase. Detailed descriptions of Franciscan rocks similar to those found in this area may be found in many articles on California geology.

The serpentine is altered peridotite or pyroxenite. Two types of serpentine occur in the outcrops. The difference between these is due mainly to shearing of the mass. Highly sheared serpentine is blue, light blue, or white in color and is the most abundant. It breaks into thin flakes along innumerable shear planes. The other type of serpentine is dark green in color, solid, and contains abundant bastite pseudomorphs up to 0.5 inch in size. The solid serpentine occurs as rounded boulders up to 60 ft in diameter within the sheared mass. The boulder-like serpentine is found both as scattered masses and in groups resembling dikes or lenses. No detailed petrographic examination was made of the serpentine in the map area.

Structural relations--The San Andreas Fault zone borders the area on the southwest and is the main feature controlling the minor structures in this region. The Franciscan and Eocene formations are in fault contact except for the northern remnant of the Eocene formation which lies unconformably upon the Franciscan formation. The Franciscan formation itself is very much sheared and contorted in this area but dips generally to the southwest. The Eocene formation is a northeastward dipping homocline terminating in a syncline near the edge of the Recent alluvium. This structure in the Eocene formation continues for more than four miles to the southeast of the map area. There are many minor flexures in the Eocene sediments, but the structure as a whole is well defined.

The northern two-thirds of the serpentine body separates the Franciscan sediments from the Franciscan basalts and diabases. This serpentine may possibly be a remnant of an original dike or sill. The southern third of the serpentine body is entirely surrounded by the Eocene formation. The important point here is that the serpentine body does not disturb the homoclinal dip of the Eocene formation. In other words, the serpentine body is a plug-like intrusion into the Eocene homocline. At least 1500 ft of the Eocene formation has been penetrated by the serpentine. Sandstone beds in the Eocene formation are shown on the geologic map by dots. These beds end abruptly against the serpentine with no room for having been turned aside. It is concluded that part of these beds have been cut off and removed by the serpentine plug.

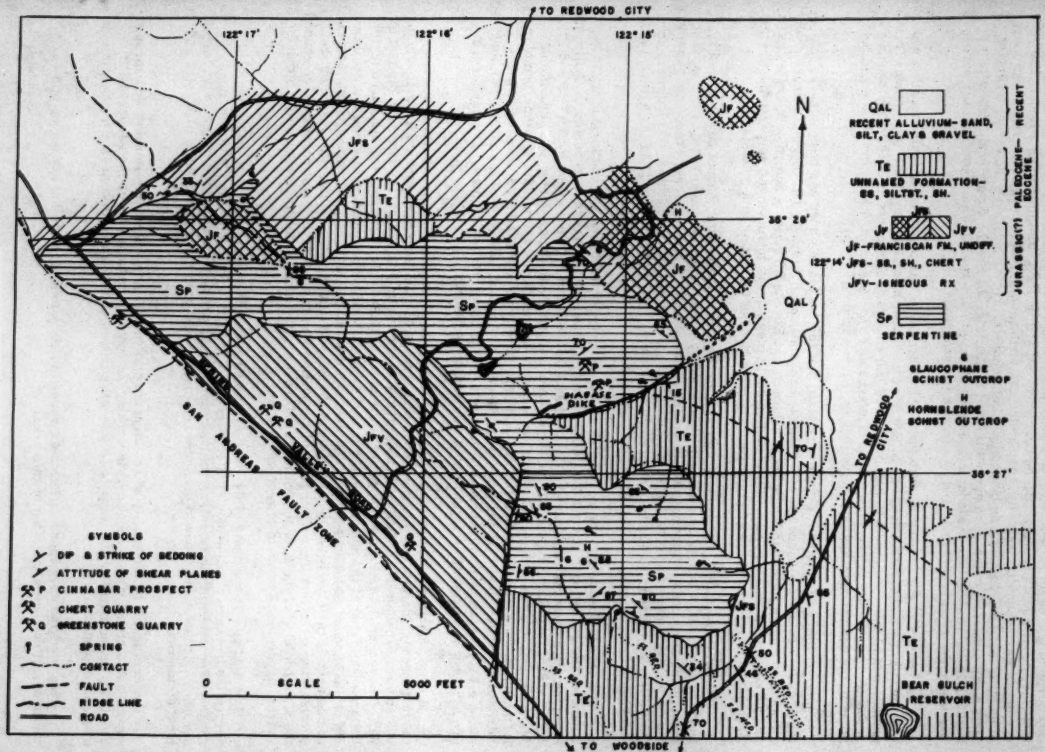


Fig. 1--Serpentine intrusion southwest of Redwood City, California

Serpentine contact--The border of the serpentine is shown in most places with a simple contact line, but it would probably also be correct to show it on the geologic map as a fault. The contact of the serpentine body with the Franciscan formation was observed in several locations. In most of these the contact was obviously a fault contact. In two localities, however, baking effects were observed which were not obliterated by faulting. In one the Franciscan rock was a hard shale and in the other a sandstone. Baking effects to a distance of six feet from the serpentine were observed in the shale and to a foot in the sandstone.

The contact of the serpentine with the Eocene formation was observed in four localities and was found to be a shear zone from 20 to 200 ft wide. The material in the shear zone grades from undisturbed Eocene sediments to highly sheared and contorted sediments, to very highly sheared serpentine and finally to serpentine as described above. No baking or other alteration could be found in the sediments other than the crushing of large grains.

Interpretation of geology--Evidence is plain that the serpentine body has been intruded into the Eocene formation. There are two possible explanations of this: (1) The original intrusion of ultra basic magma penetrated both the Franciscan and Eocene formations and cooled, crystallized, and serpentinized in one period. (2) The ultra basic magma was intruded and serpentinized in the Franciscan formation and later re-intruded into the Eocene formation in a cold state.

The first possibility, intrusion of magma into the Eocene formation, cannot be disproved by field evidence, since baking or other effects caused by magma may be destroyed by later movement of the serpentine. This possibility would imply a post Eocene or at least Paleocene age for the magmatic intrusion. The latest date of ultra basic magma intrusion reported elsewhere in the California coast ranges is upper Jurassic or possibly lower Cretaceous [TALIAFERRO, 1943a and b].

The second possibility, the re-intrusion of cold serpentine into the Eocene formation, is supported by the gradational shear zone. Cold intrusion of serpentine has been reported in California into formations as young as Miocene [TALIAFERRO, 1943a and b]. In a paper by YATES and HILPERT [1946], evidence is given for re-intrusion of serpentine in upper Cretaceous, late middle Miocene, and Pliocene times. The big blue serpentinous member of the middle Miocene Temblor formation in the Coalinga area [CLARK, 1935] may have been deposited from erosion of a re-intruded serpentine body. In the area under discussion original intrusion of the ultra basic magma into the Franciscan formation probably occurred in late upper Jurassic times. The re-intrusion occurred here at least after deposition of the Eocene sediments.

Miocene marine sediments unconformably overly the Eocene formation 2.5 miles southeast of the map area on the extension of the homoclinal structure. The Eocene sediments have dips up to 90° and are occasionally overturned, while the Miocene sediments ordinarily only have dips up to 25°. These generalizations do not apply to areas more than four miles from the map area or to the area southwest of the San Andreas Fault. The Eocene-Miocene unconformity and the gentle dip of the Miocene sediments indicate that the period of strongest post-Cretaceous folding occurred in this area in the time between deposition of the Eocene and Miocene sediments. It is most reasonable to assume that the re-intrusion of serpentine was caused by the same forces which caused the strong folding of the Eocene sediments. Therefore, the most probable age of the re-intrusion is from uppermost Eocene to lowermost Miocene.

Conclusion--On the basis of the data mentioned above, it seems likely that re-intrusion of serpentine has been a rather common occurrence in the geologic past in the California coast ranges. The cause of the re-intrusion has been renewed pressure upon buried or partially buried serpentine bodies. The renewed pressure has undoubtedly been closely related to orogenies and/or local disturbances.

Realization of the possibility of re-intrusion may be of some value when working with mineral deposits associated with serpentine. In working out tectonic histories involving serpentine it should be recognized that the serpentine may have moved considerable distances after the time of original emplacement.

Acknowledgments--Appreciation is expressed to Benjamin M. Page for his advice and encouragement during the mapping of this area.

References

BRANNER, J. C., J. F. NEWSOM, and R. ARNOLD, U. S. Geol. Survey Atlas, Santa Cruz folio, no. 163, 1909.

CLARK, BRUCE L., Tectonics of the Mount Diablo and Coalinga areas, middle coast ranges of California, Geol. Soc. Amer. Bull. 46, pp. 1025-1078, 1935.

MARTIN, LOIS T., Upper Cretaceous Foraminifera from the Chico formation, San Francisquito Creek, Calif., Proc. Geol. Soc. Amer. 1936, p. 394, 1937.

TALIAFERRO, N. L., Geologic history and structure of the central coast ranges, Calif., Calif. Dept. Nat. Resources, Div. Mines Bulletin 118, 1943a.

TALIAFERRO, N. L., Franciscan-Knoxville problem, Bull. Amer. Assoc. Pet. Geol., v. 27, pp. 109-219, 1943b.

YATES, R. G., and L. S. HILPERT, Quicksilver deposits of the eastern Mayacmas district, Lake and Sonoma Counties, Calif., Calif. J. Mines and Geology, v. 42, pp. 231-286, July, 1946.

3737 Telegraph Road,
Ventura, California

(Communicated manuscript received December 4, 1950;
open for formal discussion until November 1, 1951.)

DISCUSSION OF

"EROSION PAVEMENT, ITS FORMATION AND SIGNIFICANCE"
by W. C. LOWDERMILK and H. L. SUNDLING

[Trans., v. 31, pp. 96-100, 1950]

Louis C. Peltier (3404 Twenty-Fifth St., S.E., Washington 20, D. C.)--Lowdermilk and Sundling have provided a welcome contribution to the knowledge of an important geologic and pedologic process. Examples of erosion pavement in differing scales are commonly to be found in nature. Among these are the cailloutis zones or pebble bands reported from the loessial deposits of western Europe by BREUIL [1934] and summarized by ZEUNER [1945], the boulder-strewn slopes of such mountains as the northern Appalachians [DENNY, 1938; PELTIER, 1949] or the Erzgebirge [BÜDEL, 1937] which once lay within the realm of periglacial climates, and the barren blockfields of Scandinavia [HÖGBOM, 1926], central Germany [BÜDEL, 1937], eastern United States [SMITH, 1949], and elsewhere.

The cailloutis zones in the loess may be explained as concentrations of pebbles initially included in the soil by mass movement or running water, and then concentrated in one horizon by the selective pluvio-fluvial erosion of fine-grained particles. The boulder-strewn slopes which mantle the Appalachian Mountains of Pennsylvania consist of a veneer of angular fragments lying over a congeliturbate deposit. These slopes are characteristic of the Dekalb stony loam soils of the Susquehanna Valley, Pennsylvania [PELTIER, 1949]. They are similar in appearance to the soils with erosion pavement developed in the Dekalb stony loam of Clearfield County, Pennsylvania, described by SHAW [1929]. The pavement which developed on the surface of the rubble must have formed after the manner described by Shaw and by Lowdermilk and Sundling. This material was derived by frost-riving from the rock which lies at higher elevations on the slope. Existing exposures show the congeliturbate to be an essentially homogeneous mixture of fragments of all sizes. As long as the process of frost-shattering, frost-heaving, and soil-flowage continued, any selective erosion which might have taken place at the surface must have been obscured. After the cessation of congeliturbation the selective erosion of the pluvio-fluvial regime must have become effective and a concentration of coarse fragments at the surface resulted. Wherever this process became arrested by encroaching vegetation, a boulder-strewn slope was formed. If, however, selective erosion was permitted to continue, as in some drainageways, all fine-grained material may have been washed away to a depth of four to eight feet. These drainageways exist today as barren, treeless blockfields. The base of the eluviated zone is marked, in many places, by the occurrence of thin deposits of stratified sand.

The effort, by the authors, to draw a fine distinction between erosion pavement, as described by SHAW [1929], and desert pavement, as described by FREE [1911] and others, seems unnecessary. The desert pavement of Free is essentially a lag-gravel surface formed by deflation. However, Free also mentioned a pavement near Hazen, Nevada, which he believed was formed by flowing water. It is likely that many other desert pavements were also produced by running water. The critical element in all instances seems to be exposure of the ground to surface flow through the absence of such a protective medium as a plant cover. This may be produced either by the deforestation and cultivation by man or by climatic changes which man is powerless to control. Both of these pavements are residual pavements formed in one instance by sheet wash and rill wash, and in the other instance by deflation. Other paved surfaces, the product of selective erosion by a river or by the tide, occur along the Delaware River and its estuary in Pennsylvania. Insofar as they are all the product of selective erosion they are all erosion pavements. Perhaps we should recognize deflation pavements, sheet-wash pavements, and channel pavements.

The authors have correctly interpreted the erosion pavement as indicative of an increased rate of erosion. The possibility of misunderstanding over the unqualified term "accelerated erosion" must, however, be recognized. There may be accelerated erosion on the hill slopes and there may be accelerated erosion of the stream channels. They may not be compatible. Indeed, the increase of slope erosion may so load the streams as to lead to a cessation of channel erosion and the deposition of channel filling. Conversely, the decrease of slope erosion may lead to channel scour.

The authors' interpretation of erosion pavement as evidence of accelerated slope erosion may be applied to the interpretation of cobble concentrations in the Pleistocene congeliturbate deposits. These concentrations must mean that episodes of accelerated erosion followed the episodes of severe frost-action in Pleistocene time. Perhaps these episodes correspond with those of sand and silt deposition in some of the river valleys. On the other hand, river terraces in the northern Appalachians, even in unglaciated drainage basins, correlate with glacial outwash terraces and indicate that the valleys became choked with rubble during the cold episodes of the Pleistocene. This regime differed from that simulated by Lowdermilk and Sundling in that, during the cold Pleistocene episodes, mass movement in slopes probably predominated over pluvio-fluvial erosion, both as a process and in its total effect.

The erosion pavement may be interpreted to indicate a change in the local regime so that the rate of pluvio-fluvial erosion exceeds the rate of weathering of the surface. Its significance must therefore be similar to that of a bedrock exposure.

References

BREUIL, H., De l'importance de la solifluction dans l'étude des terrains quaternaires du nord de la France et des pays voisins, Rev. Géogr. Phys. Géol. Dynamique, v. 7, pp. 269-284, 1934.

BÜDEL, J., Eiszeitliche und rezente Verwitterung und Abtragung im ehemals nicht vereisten Teil Mittel-Europas, Pet. Mitt., Erg., no. 229, 71 pp., 1937.

DENNY, C. S., Glacial geology of the Black Rock Forest, Black Rock Forest Bull., no. 8, pp. 1-70, 1938.

FREE, E. E., The movement of soil material by the wind, with a bibliography of eolian geology by S. C. Stuntz and E. E. Free, U. S. Dept. Agr., Soils Bull., no. 68, 272 pp., 1911.

HÖGBOM, B., Beobachtungen aus Nordschweden über den Frost als geologischer Faktor, Bull. Geol. Inst., Upsala, v. 20, pp. 243-279, 1926.

PELTIER, L. C., Pleistocene terraces of the Susquehanna River, Pennsylvania, Pa. Geol. Surv., 4th ser., Bull. G. 23, 158 pp., 1949.

SHAW, C. F., Erosion pavement, Geogr. Rev., v. 19, no. 4, pp. 638-641, 1929.

SMITH, H. T. U., Physical effects of Pleistocene climatic changes in nonglaciated areas; eolian phenomena, frost action, and stream terracing, Bull. Geol. Soc. Amer., v. 60, pp. 1485-1516, 1949.

ZEUNER, F. E., The Pleistocene period, its climate, chronology, and faunal successions, R. Soc., London, 322 pp., 1945.

DISCUSSION OF

"FLUID RESISTANCE OF COMPOSITE ROUGHNESS"
by H. A. EINSTEIN and R. B. BANKS

[Trans., v. 31, pp. 603-610, 1950]

Ralph W. Powell (Ohio State University, Columbus, Ohio)--This paper presents a very interesting approach to the subject of composite roughness, but the writer cannot believe that the answer is quite so simple. For any given roughness, it is well known that Chezy's C is a function of the hydraulic radius. Therefore, the authors' T/V^2, which is w/C^2, will also be a function of the hydraulic radius. Tables 1 and 2 do not give the values of R, but they were obviously not all the same, and it would seem that variations in R would be an important cause of scatter of points in Figure 2. For this same reason it would seem that a set of points giving parallel straight lines as in Figure 2, might be obtained by chance.

In the light of this paper, the writer has investigaged the results of his own experiments with various spacings of 1/8- and 1/4-inch square strips or battens placed down the sides and across the bottom of a rectangular flume. As has already been reported [POWELL, 1950], it was found that the resistance could be fairly well represented by

$$C = 42 \log_{10} (R/\epsilon) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (19)$$

and that of the flume without the battens by

$$C = 42 \log_{10} (R/C) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (20)$$

In order to eliminate the effect of other factors, it will be assumed in what follows, that the mean velocity in the smooth flume is 2.5 ft/sec, the hydraulic radius 0.125 ft, and the kinematic

Table 3--Computation of resistance of writer's battens

Roughness	Number of strips in 40 inches		ϵ	C	$62.4/C^2$	$T/V^2 - 0.00417$
	1/8 inch	1/4 inch				
XI	0	1	0.00311	67.4	0.01375	0.0096
I	0	2	0.00571	56.3	0.01969	0.0155
II	0	4	0.01029	45.5	0.03007	0.0259
III	0	8	0.01415	39.7	0.03952	0.0353
IV	8	8	0.01597	37.5	0.04429	0.0401
V	12	4	0.01358	40.5	0.03807	0.0339
VI	14	2	0.01133	43.8	0.03253	0.0284
VII	16	0	0.00876	48.5	0.02654	0.0224
VIII	8	0	0.00555	56.8	0.01934	0.0152
IX	4	0	0.00312	67.3	0.01377	0.0096
X	2	0	0.00163	79.2	0.00996	0.0058

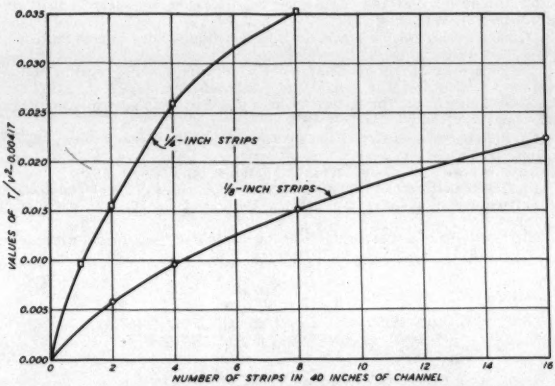


Fig. 4--Relation of T/V^2 to number of strips

viscosity of the water 0.0000125 sq ft/sec. These values are approximately in the middle of the range covered by the experiments. Then $R = 4\,R\,V/\nu = 100{,}000$, which agrees with (20) when C = 122.3. Then for the smooth channel, $T/V^2 = 62.4/122.3^2 = 0.00417$ lb sec^2/ft^4. This is not so very much different from the 0.00505 or 0.00506 found by the authors. Table 3 gives the number of 1/8- and 1/4-inch battens per 40 inches of length of channel and the values of ϵ found by the writer, and from (19) with R = 0.125 ft, the value of C. Then the value of $T/V^2 = 62.4/C^2$ is computed, and this quantity minus 0.00417 should be the measure of the resistance of the battens alone.

Figure 4 shows a plotting of these values of $T/V^2 - 0.00417$ against the number of strips per 40 inches. It is seen that these lines are far from straight. In fact, they could not be because the maximum roughness occurs when the spacing is about 12 times the height of the batten, or three inches for the 1/4-inch battens and 1.5 inches for the 1/8-inch battens. In 40 inches this would give 13.3 of the former and 26.7 of the latter. The curves look as if they might have maxima at these points. Probably if the authors' tests had been extended to densities of 30 or 40 pegs per square foot, their lines would have shown a similar curvature.

Roughness IV is a combination of Roughnesses III and VIII. But 0.0353 + 0.0152 = 0.0503, which is a good deal more than the 0.0401 given by Roughness IV. Similarly the curve of Figure 4 gives 0.0192 for 12 1/8-inch strips, and Roughness II gave 0.0259 for four 1/4-inch strips. Adding 0.0259 and 0.0192 gives 0.0451, which is much more than the 0.0339 given by Roughness V. The

curve gives 0.0208 for 14 1/8-inch strips, and Roughness I gave 0.0155 for two 1/4-inch strips. The sum is 0.0363, which is much more than the 0.0284 given by Roughness VI for the same combination. Therefore, the experiments made by the writer do not seem to bear out the authors' thesis.

Reference

POWELL, RALPH W., Resistance to flow in rough channels, Trans. Amer. Geophys. Union, v. 31, pp. 575-582, 1950.

H. A. Einstein and R. B. Banks (Fluid Mechanics Laboratory, University of California, Berkeley, California, Authors' closure)--Powell's discussion is most valuable because it is based on a misunderstanding of the subject matter described in the original paper which may have been caused by the presentation of the paper. The authors did not intend to claim proportionality of the peg-resistance to the peg-density for the entire range of peg-densities from zero to complete coverage of the bed. This "linearity" was more or less incidental and convenient as it led to an easy method of presentation. It holds only as long as there is no mutual interference between the individual roughness elements. For all higher densities this "linearity" disappears as Powell pointed out.

The "linearity" which represents the basic idea of the paper is the independence and the ability to be superimposed of the different types of frictional devices. These devices are, accordingly, the block surface, the pegs and the block offset and all apply to the same bed surface.

Actually, Powell's example serves as an excellent confirmation of this main linearity. An analysis was made of the data recorded by POWELL [1946]. This analysis consists of resolving the resistance caused by the strips and by the sidewalls and bottom surfaces. The results were then expressed in terms of the strip geometry and applied to the example given in Table 3. These results are plotted in Figure 5, together with the points calculated by Powell. It may be seen

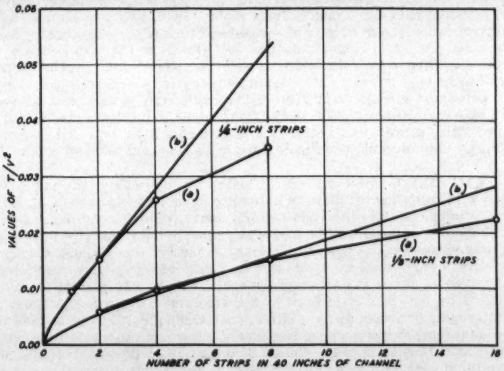


Fig. 5--Relation of T_o/V^2 to number of strips

from Figure 5 that the two curves coincide very closely when the number of 1/4- and 1/8-inch strips per 40 inches of channel is less than 4 and 8, respectively. The details of this calculation, which avoids the use of any semi-empirical parameters and especially the explanation of the bend of the curve near the origin, will be given elsewhere.

Reference

POWELL, R. W., Flow in a channel of definite roughness, Trans. Amer. Soc. Civ. Eng., v. 111, pp. 531-554, 1946.

LETTER TO THE EDITOR

HYDROLOGY COMES OF AGE

The development of hydrology since the period of Perrault (1608-1680) and Mariotte (1620-1684) has embraced the gradual evolution of an important Earth science whose genesis is associated with the intellectual curiosity of the very earliest scientists regarding the origin of springs and the correlation of rainfall-runoff phenomena.

The emergence of well-defined principles of water behavior has been notably hastened by engineering developments of the past 20 years relating to better utilization of water resources including the control of runoff patterns which are inimical to the best social and technologic advances. Contemporary hydrologic literature is exceedingly voluminous. The recent publication of four new textbooks on hydrology, the first in virtually some 30 years of American technical literature, reflects the pressing need of evaluating current knowledge and of making possible its dissemination in convenient form to the practicing hydrologist as well as to the college student.

In 1904 when the late Daniel W. Mead released his "Notes on hydrology," the first American treatment of the subject, he adopted the preface "Hydrology - The fundamental basis of hydraulic engineering." Mead, who was later affectionately called "The Father of American Hydrology," did much to implant this fundamental idea in successive classes of civil engineering students who studied under him at the University of Wisconsin.

Hydrology, one of the basic Earth sciences, is closely allied with meteorology and geology as well as with soil physics, chemistry, and oceanography. Hydrology has attained stature and importance as its broad and relevant role in all branches of hydraulic engineering has become more and better recognized. Current problems dealing with flood control, water supply, and stream pollution bear out the utility of hydrologic advances of the past decade. The phenomenal growth of the literature of hydrology has been stimulated by noteworthy research programs conducted by governmental agencies and schools and attests to the rapid strides that have been made in the development of this science. Although hydrology is now more firmly established than even before, it is still in its formative stages, and seasoned maturity cannot be expected for some years. This is because much yet remains to be investigated and to be well outlined and proportioned.

Early hydrology--The two eminent French physicists Pierre Perrault and Edme Mariotte are generally credited with being the founders of scientific hydrology because of the observational work they conducted in connection with rudimentary rainfall-runoff relations. Beardmore's "Manual of hydrology" which appeared in 1862 was probably the first important work in English and its influence was widespread in Europe for many years. In this country during the same period many pioneering efforts were made by prominent hydraulicians and hydrologists laboring in closely related fields. The report on the Physics and Hydraulics of the Mississippi River by Humphreys and Abbot in 1861 has become a classic work in American river hydrology. The beginning of the systematic stream-gaging program of the United States Geological Survey in 1889 represents one of the most significant movements made to implement study and research in hydrology in America. Equally important was the creation of the United States Weather Bureau in 1891. Abroad, the investigations of Wollny in Germany from 1879 to 1898 on the physical properties of soil were pioneering studies in soil physics in its relation to hydrology and undoubtedly initiated research that has culminated in the present-day theory of infiltration.

The era of empiricisms, 1900-1921--Mead did much to establish the study of hydrology on a firm basis in our engineering schools. A consulting hydraulic engineer of high repute as well as a capable teacher, he was one of the first to appreciate that hydrologic data were a prerequisite for good hydraulic engineering design. As a teacher he worked diligently to convey this philosophy to his students and one of them, Adolph E. Meyer, further strengthened early American hydrology with his textbook and writings. Hence, the very fabric of the science was inextricably associated with the definitive works of these two hydrologists.

Mead and Meyer were the precursors of a school of empirical hydrology, for estimating runoff

was hardly a science but rather an art that was largely dependent upon judgment and experience in selecting coefficients of runoff. The physical basis for the determination of runoff volumes and rates was not well known nor were there research programs of any consequence on small watersheds to guide the engineer or to demonstrate the effects of soil, cover, or land use. The flood formulas of Talbot, Myers, and Fuller, and Vermuele's expression for annual runoff exemplify the empirical basis for the practice of hydrology in this period.

The disastrous flood on the Miami River in 1913 focused need to study means for abatement of this perennial danger. To provide basic data and clarify previously-held concepts of open-channel flow and certain manifestations of unsteady flow such as the hydraulic jump, a comprehensive program of study and research was begun dealing with such manifold topics as maximum storm rainfall and rainfall-runoff relations. Houk did much valuable work for the Miami Conservancy District which other organizations facing similar problems could well have emulated. Instead hydrologic activity lapsed in the decadent period of the 1920's.

Lethargy, 1921-1931--The vigorous efforts made by the first American hydrologists were not continued by younger men and there was a period of inactivity approximately from 1921-1931 that enervated the fiber of hydrologic thought and endeavor so that American hydrology became debilitated and torpid. One reason for this condition is that there was little motivation for further study of hydrologic principles except insofar as they could be applied to large projects like flood control. Integrated water-resources planning for the nation had not as yet been introduced. Several exceedingly important events, however, took place. One was the creation of the Section of Hydrology of the American Geophysical Union in 1930. Another was the publication of the monumental report of the Committee on Rainfall and Runoff of the Boston Society of Civil Engineers in the same year. This report represented an outstanding contribution to existing principles of flood hydrograph analysis. During this same period many runoff investigations were conducted by the Bureau of Agricultural Engineering of the United States Department of Agriculture of small drainage areas in all parts of the country. The methodologies of analysis were not equal, however, to those developed in the 1930's. Furthermore, continuous recording instruments were not widely used and the data secured were not of high quality.

Empiricism to rational analysis, 1932-1950--The emergence of fluid mechanics from hydraulics has its counterpart in the new hydrology that has been very largely developed in the past two decades. The observations of the Committee on Floods of the Boston Society of Civil Engineers that "the peak flow varies directly with the total flood runoff and that the total flood period is a constant for a given point on a stream" provided the logical prelude for the thought-provoking concepts regarding the unit hydrograph that were enunciated for the first time by Sherman in 1932. He demonstrated the use of the unit hydrograph for translating rainfall excess into a hydrograph of surface runoff. Since that time the principle of the unit hydrograph has pervaded all research in flood hydrology. To Sherman, therefore, in large measure is due the credit for the re-emergence of applied hydrology and for the introduction of methodologies useful in the analysis of rainfall-runoff records and the synthesis of river hydrographs from precipitation data. Although the concept of the unit hydrograph represented a signal advance in hydrologic thought, the problem of rational determination of rainfall excess still confronted the practicing hydrologist and continues not in minor degree to plague the profession today. Bernard in 1934 introduced the distribution graph which embodies the essential properties of the unit hydrograph but expresses the proportion of total runoff occurring in different time intervals instead of flow rates.

As the result of the publication of his "The role of infiltration in the hydrologic cycle" in 1933, Horton can be said to have initiated the most successful approach to date in the problem of determining rainfall excess. It remained for his masterful treatise "Surface runoff phenomena, Publication 101" to complete the setting for a steady and far-reaching series of studies by other hydrologists that has continued since that time. Horton's classic work did much to bring about the advent of orderly and systematic thinking as to the fundamental character of a stream hydrograph and served to inspire others to very competent achievements in rainfall-runoff relations in the past ten years. Increasing recognition of the importance of the infiltration approach towards determination of water abstractions encouraged prominent investigators in the period since 1933 to study the nature of the infiltration curve in its relation to runoff from controlled plats, small watersheds, and large drainage areas. The Transactions of the American Geophysical Union record many important contributions by others. The difference in the methodologies and the divergency of the results indicates that these researches are only preliminary in their scope and much progress is yet to be made before water abstractions out of rainfall will be more determinate. The growing trend to rationalize rainfall-runoff relationships and to avoid empirical formulas has encouraged important experimental investigations of runoff from urban areas and airports in recent years.

The science of hydrology is today commanding increased respect from those civil engineers who have to deal with water in any of its multifarious aspects. Recent publication of the new Hydrology Handbook of the American Society of Civil Engineers confirms the need for a convenient reference work to aid the hydraulic engineer in his study and application of this subject. The requirements of flood-stage prediction services have made necessary pronounced expansion and densification of the hydrometeorological network. The intricate relations between hydrology and meteorology have stimulated comprehensive hydrometeorological studies by the U. S. Weather Bureau and the Corps of Engineers of the Department of the Army that augur well for future hydraulic developments.

Notable advances in recent years have been developments involving the use of radio for automatic transmission of stream stages and rain catches and radar detection of approaching storms. The art of measuring stream flow is constantly being reviewed and appropriate betterments effected as funds permit. The requirements of modern warfare involving artificial flooding for offensive as well as defensive actions indicate an ever-widening scope of application in this era.

Education has been improved by perceiving the association of hydrology with other sciences. This is especially true regarding the fields of ground water and geology, and soil mechanics and soil physics as affecting infiltration. Courses in hydrology are being incorporated in more civil engineering and other curricula.

The statistical approach in the interpretation and correlation of data and the extension of flood-frequency curves is gaining increased recognition. Even soil erosion, silting of reservoirs, and geomorphology are linked with hydrology. It seems reasonable to expect that present and future needs of our nation for more and better hydrologic data in relation to water supply, irrigation, flood control, navigation, and related problems will more than ever assert the continuing role that this science will play in our water economy. Hydrology has come of age.

Milton O. Schmidt

University of Illinois,
Urbana, Illinois

BIBLIOGRAPHY

BIBLIOGRAPHY: GENERAL

BARTELS, JULIUS, Geophysics (Geophysica), I, II, Naturf. Mediz. Deutschl., 1939-1946, v. 17, 18, Wiesbaden, Dieterich'sche Verlagsbuchh., 237 pp., 307 pp., 1948 (in German) [abstr. in Appl. Mech. Rev., v. 4, no. 3, p. 196, 1951].

CHILDE, V. G., Comparison of archaeological and radiocarbon datings, Letter in Nature, London, v. 166, pp. 1068-1069, 1950 [abstr. in Phys. Abstr., v. 54, no. 639, p. 253, 1951].

PAUL, M., Contribution to the problem of solar influence on geophysical events, Geofis. Pura Appl., v. 17, pp. 13-36, 1950 (in German) [abstr. in Phys. Abstr., v. 54, no. 639, p. 253, 1951].

RAMAN, C. V., New physics, Philosophical Library, New York, 144 pp., 1951.

SCHEFFER, VIKTOR, and KÁROLY KANTÁS, A Dunántúl regionális geofizikája (Die regionale Geophysik Transdanubiens), Földtani Közlöny, Budapest, v. 79, no. 9-12, pp. 327-360, 1949 (in Hungarian with summary in German).

ZEUNER, F. E., Dating the past by radioactive carbon, Nature, London, v. 166, pp. 756-757, 1950 [abstr. in Phys. Abstr., v. 54, no. 639, p. 253, 1951].

BIBLIOGRAPHY: GEODESY

ANDREEV, B. A., Prostoi metod rascheta geofizicheskikh anomalii na vysote, Vsesoiuznyi Nauchno-Issledovatel'skii Inst., Razvedochnoi Geofiz., no. 3, pp. 6-10, 1950.

ANDREEV, B. A., Ob usloviiakh primenimosti formul dvukhmernoi zadachi pri interpretatsii magnitnykh i gravitatsionnykh anomalii, Vsesoiuznyi Nauchno-Issledovatel'skii Inst., Razvedochnoi Geofiz., no. 3, pp. 3-6, 1950.

BAETSLÉ, P. L., Systématisation des calculs numériques des matrices, Bull. Géod., no. 19, pp. 22-41, 1951.

BIESHEUVEL, H., The adjustment of traverse nets, Emp. Surv. Rev., v. 11, no. 79, pp. 24-28, 1951.

BULANZHE, IU. D., Novoe znachenie uskoreniia sily tiazhesti dlia Geofizicheskogo Instituta Akademii Nauk SSSR, Geofiz. Inst., no. 5, v. 132, pp. 76-93, 1949.

BULANZHE, IU. D., Predvaritel'nye rezul'taty opredeleniia gravimetricheskogo punkta pervogo Klassa v selenii obi-garm, Akademiia Nauk SSSR, Geofiz. Inst., no. 5, v. 132, pp. 94-99, 1949.

BULANZHE, IU. D., Novaia gravimetricheskaia sviaz Vsesoiuznogo nauchno-issledovatel'skogo Instituta Metrologii s Pulkovom, Akad. Nauk SSSR, Geofiz. Inst., no. 5, v. 132, pp. 100-115, 1949.

CAHIERRE, L., Méthodes de nivellement géométrique de précision--Application au franchissement des estuaires, Bull. Géod., no. 19, pp. 42-56, 1951.

COOPER, R. I. B., Variations in the length of the day, Nature, v. 167, no. 4243, pp. 292-298, 1951.

COX, J. F., La projection équidistante pour deux points (The doubly equidistant projection), Bull. Géod., no. 19, pp. 57-60, 1951.

CUNIETTI, M., Sulla magnetizzazione di gravimetri astatici, Riv. Geofis. Applicata, Milano, v. 11, no. 2, pp. 103-107, 1950 (summary in English).

DANILOV, V. V., Metody obrabotki povtornykh geodezicheskikh izmerenii, provodimykh v tseliakh vyiavteniia gorizontal'nykh deformatsii zemnoi kory, Akad. Nauk SSSR, Geofiz. Inst., no. 5, v. 132, pp. 115-120, 1949.

EDEN, J. A., Point identification on air photographs, Emp. Surv. Rev., v. 11, no. 79, pp. 16-18, 1951.

EGEDAL, J., Report on the diurnal variation of the height difference between fixed points, Bull. Géod., no. 18, pp. 452-453, 1950.

HEISKANEN, W., On the isostatic structure of the Earth's crust, Ann. Acad. Sci. Fennicae, Ser. A III, no. 22, 60 pp., 1950 [abstr. in Phys. Abstr., v. 54, no. 638, p. 171, 1951].

INDIA, SURVEY OF, Technical report, 1948-1949, Geod. and Training Circle, Dehra Dun, 155 pp. + 35 pl., 1950.

INOUE, E., and H. ŌNO, The horizontal displacements of the Earth's crust accompanying the great Kwanto Earthquake 1923, Bull. Geogr. Surv. Inst., Japan, v. 2, pt. 1, pp. 61-72, 1950.

JUDICE, A., Calcul pratique de l'aplatissement de la terre et de la pesanteur équatoriale, Geofis. Pura Appl., Milano, v. 18, pp. 1-8, 1950.

KAŠPAR, JAN, Krakovjany v geodesii, Zeměměřický Obzor, v. 11/38, no. 10, pp. 162-165, 1950.

KUKKAMÄKI, T. J., Report on the causes of error affecting levelling, Bull. Géod., no. 18, pp. 427-431, 1950.
KUKKAMÄKI, T. J., Report on a simplified method for an approximate comprehensive adjustment of contiguous level networks, Bull. Géod., no. 18, pp. 442-444, 1950.
LAUF, G. B., A new method for the adjustment of a network of triangulation, Emp. Surv. Rev., v. 11, no. 79, pp. 19-24, 1951.
MARUSSI, A., Les principes de la géodésie intrinsique, Bull. Géod., no. 19, pp. 68-76, 1951.
MIDDLETON, W. E. KNOWLES, The attenuation of contrast by the atmosphere, Photogrammetric Eng., pp. 663-672, 1950.
MORELLI, C., Collegamento gravimetrico Padova-Trieste e rilieveo gravimetrico regionale del veneto centro-orientale, Riv. Geofis. Applicata, Milano, v. 11, no. 2, pp. 85-102, 1950 (summary in English).
PEŇÁZ, JOSEF, Novodobé geodetické pomůcky pro územní plánování a lidovou správu, Zeměměřicky Obzor, v. 11/38, no. 11, pp. 169-174, 1950.
ROBBINS, A. R., Deviation of the vertical, Emp. Surv. Rev., v. 11, no. 79, pp. 28-36, 1951.
RUNE, G. A., Report on Kukkamäki's method for computing the levelling effect of the atmospheric refraction, Bull. Géod., no. 18, pp. 432-433, 1950.
RUNE, G. A., Report on gravity anomalies and levelling, Bull. Géod., no. 18, pp. 434-435, 1950.
RUNE, G. A., Report on some in Sweden observed irregularities in the Fenno-Scandian post-glacial upheaval of land, Bull. Géod., no. 18, pp. 436-437, 1950.
RUNE, G. A., Report on Kukkamäki's simplified method for an approximate comprehensive adjustment of contiguous level networks, Bull. Géod., no. 18, pp. 445-447, 1950.
RUNE, G. A., Report on levelling and moon-sun diurnal oscillation of the vertical, Bull. Géod., no. 18, pp. 448-449, 1950.
SIMONSEN, O., Report on the secular movement of ground observed in Denmark by means of comparing precise level networks of 1885-1905 and 1938-1948, Bull. Géod., no. 18, pp. 438-444, 1950.
SIMONSEN, O., Report on the astronomical diurnal correction in the new Danish precise level network, Bull. Géod., no. 18, pp. 450-451, 1950.
SMITH, H. M., The determination of time and frequency, Inst. Elect. Eng., Paper 1054, 11 pp. [abstr. in Phys. Abstr., no. 637, p. 8, 1951].
TIENSTRA, J. M., The normal section of the ellipsoid, Bull. Géod., no. 19, pp. 7-21, 1951.
TSUBOKAWA, I., Die Ausgleichung von Polygonzügen nach der Methode der kleinsten Quadrate, Bull. Geogr. Surv. Bur., v. 1, pt. 1, pp. 1-8, 1948 (in Japanese with summary in German).
VENING MEINESZ, F. A., and Others, New formulas for systems of deflections of the plumb-line and Laplace's theorem, Bull. Géod., no. 19, pp. 61-67, 1951.
VIGNAL, J., Comptes rendus des séances de travail de la Section II. Nivellements, de la Association Internationale de Géodésie à l'Assemblée Générale d'Oslo, (Août 1948), Bull. Géod., no. 18, pp. 403-426, 1950.
WRIGHT, J. W., Reconnaissance mapping from trimetrogon photographs in the Anglo-Egyptian Sudan, Emp. Surv. Rev., v. 11, no. 79, pp. 2-16, 1951.

BIBLIOGRAPHY: SEISMOLOGY

DEBRACH, JEAN, L'agitation microseismique d'origine océanique, Rev. Géogr. Marocaine, pp. 9-26, 1949.
DUE ROJO, A., and A. GIMENO RIUTORT, El factor térmico en la génesis de los microsismos, Rev. Geofis., no. 36, pp. 321-333, 1950 (summary in English).
GERSHÁNIK, SIMÓN, Resumen de resultados sismométricos en el Observatorio de La Plata, Mem. Anual, Observ. Astronómico, Univ. Nacional de La Plata, Perú, Ser. 9, pp. 127-140, 1950.
HOMMA, S., On the propagation of dispersive seismic waves, Geophys. Mag., Central Met. Observ., Tokyo, v. 22, no. 3, pp. 209-236, 1951.
IKEGAMI, R., and F. KISHINOUYE, A study on the propagation of microseismic waves, pt. 2, Bull. Earthquake Res. Inst., Tokyo Univ., v. 28, pt. 1-2, pp. 115-119, 1950.
IKEGAMI, R., and F. KISHINOUYE, The acceleration of earthquake motion deduced from overturning of the gravestones in case of the Imaichi Earthquake on Dec. 26, 1949, Bull. Earthquake Res. Inst., Tokyo Univ., v. 28, pt. 1-2, pp. 121-128, 1950.
KANAI, K., The effect of solid viscosity of surface layer on the earthquake movements, Bull. Earthquake Res. Inst., Tokyo Univ., v. 28, pt. 1-2, pp. 31-35, 1950.
KANAI, K., A method of determining the stiffness of each story of a n-storied building, Bull. Earthquake Res. Inst., Tokyo Univ., v. 28, pt. 1-2, pp. 161-163, 1950.
KANAI, K., and S. YOSHIZAWA, Distribution of suffered frequency of earthquake damage to houses in Japan, Bull. Earthquake Res. Inst., Tokyo Univ., v. 28, pt. 1-2, pp. 167-173, 1950 (in Japanese with summary in English).

KISHINOUYE, F., and M. KOTAKA, A statistical investigation of conspicuous earthquakes in Japan during the period 1933-1943, Bull. Earthquake Res. Inst., Tokyo Univ., v. 28, pt. 1-2, pp. 109-114, 1950.

NAKANO, T., Relation between damages by earthquakes and topography, Bull. Geogr. Surv. Bur., v. 1, pt. 1, pp. 27-36, 1948 (in Japanese with summary in English).

SATÔ, Y., Transformations of wave-functions related to the transformations of coordinate systems, 1, Bull. Earthquake Res. Inst., Tokyo Univ., v. 28, pt. 1-2, pp. 1-22, 1950.

SATÔ, Y., Rayleigh waves propagated along the plane surface of horizontally isotropic and vertically aeolotropic elastic body, Bull. Earthquake Res. Inst., Tokyo Univ., v. 28, pt. 1-2, pp. 23-29, 1950.

SLATER, R. L., La prospezione sismica sottomarina per la ricerca d'idrocarburi, Riv. Geofis. Applicata, Milano, v. 11, no. 2, pp. 81-84, 1950 (summary in English).

SOLAINI, L., Sulla interpretazione delle riflessioni composte, Riv. Geofis. Applicata, Milano, v. 11, no. 2, pp. 69-80, 1950 (summary in English).

TAKAHASI, R., A short note on Kanai's formula, Bull. Earthquake Res. Inst., Tokyo Univ., v. 28, pt. 1-2, pp. 165-166, 1950.

TAKAHASHI, T., and Y. SATÔ, On the theory of elastic waves in granular substance, 2, Bull. Earthquake Res. Inst., Tokyo Univ., v. 28, pt. 1-2, pp. 37-43, 1950.

USAMI, TATSUO, On the effect of ocean upon Rayleigh waves, Geophys. Notes, Tokyo Univ., v. 3, no. 37, 5 pp., 1950.

WATANABE, A., The geomorphology of the coastal districts of the southern part of Sikoku island, and its bearing on the crustal deformations accompanying great Nankai earthquakes, Bull. Geogr. Surv. Bur., v. 1, pt. 1, pp. 37-72, 1948 (in Japanese with summary in English).

WEST, S. S., Dependence of seismic wave velocity upon depth and lithology, Geophysics, v. 15, pp. 653-662, 1950 [abstr. in Phys. Abstr., v. 54, no. 638, p. 171, 1951].

BIBLIOGRAPHY: METEOROLOGY

AMELUNG, W., Klimatische Behandlung im Mittelgebirge, Medizin-Meteorologische Hefte, Hamburg, no. 4, pp. 35-42, 1950.

BERG, H., Die Wirkung des Föhns auf den menschlichen Organismus, Proc. First Internat. Meeting Alpine Met., Int. Geofis. Italiano, Milano, pp. 24-31, 1950 (summary in English).

BINTIG, PAUL, Der Einfluss des Windes auf die Wassertemperatur des Ozeans und ihr Zusammenwirken mit der Lufttemperatur, pt. 2, Ann. Met., Hamburg, v. 3, no. 11-12, pp. 333-340 + 1 table, 1950 (summary in English).

BOSSOLASCO, M., Il foehn delle alpi italiane, Geofis. Pura e Applicata, v. 17, no. 3-4, 27 pp., 1950 (summary in English).

BURGOS, JUAN JACINTO, and ARTURO L. VIDAL, Los climas de la República Argentina según la nueva clasificación de Thornthwaite, Meteoros, Serv. Met. Nacional, Buenos Aires, no. 1, pp. 3-32, 1951 (summary in English).

COURVOISIER, P., Über das Eindringen von Schwankungen der meteorologischen Elemente in Gebäude, Archiv Met., Geophys. und Bioklim., v. 2, no. 3, pp. 162-173, 1950 (in German with summaries in English and French).

DEDEBANT, G., and Others, Enseñanzas de una nivelación barométrica, Meteoros, Serv. Met. Nacional, Buenos Aires, no. 1, pp. 55-72, 1951 (summary in French).

de RUDDER, B., Meteorologie und Krankheitsgeschehen (Autoreferat), Medizin-Meteorologische Hefte, Hamburg, no. 4, pp. 2-5, 1950.

EKHART, E., La classification des Alpes au point de vue météorologique, Proc. First Internat. Meeting on Alpine Met., Ist. Geofis. Italiano, Milano, pp. 56-61, 1950 (summary in English).

ESSENWANGER, O., Beiträge zur Statistik mittellanger Luftdruckwellen in Mitteleuropa, Berichte, Deutsch. Wetterdienst, U.S. Zone, Bad Kissingen, no. 20, 20 pp., 1951.

FONT TULLOT, INOCENCIO, Las invasiones de aire caliente africano en el archipiélago canario, Rev. Geofis., no. 36, pp. 334-349, 1950.

FREY, K., Der Dimmerföhn vom 18. Dezember 1945, Proc. First Internat. Meeting on Alpine Met., Ist. Geofis. Italiano, Milano, pp. 87-102, 1950 (summary in English).

FUJITA, T., Micro-analytical study of cold front, Geophys. Mag., Central Met. Obs., Tokyo, v. 22, no. 3, pp. 237-277, 1951.

GAMBO, K., Dynamics of the motion of the parcel of air on a rotating Earth, Geophys. Notes, Tokyo Univ., v. 3, no. 28, 21 pp., 1950.

HARE, F. KENNETH, Geographical aspects of Meteorology, in Geography in the Twentieth Century, Griffith Taylor (ed.), pp. 178-195, 1951.

HOLZAPFEL, RUPERT, Det mittlere Zustand der freien Atmosphäre über Berlin und München, Mitteilungen, Deutsch. Wetterdienst, U.S. Zone, Bad Kissingen, no. 8, 15 pp., 1951.

INOUE, EIICHI, On the pressure fluctuations in a turbulent fluid, Geophys. Notes, v. 3, no. 33, 5 pp., 1950.

INOUE, EIICHI, Prandtl Number in a turbulent fluid, Geophys. Notes, Tokyo Univ., v. 3, no. 35, 5 pp., 1950.

ISRAËL, HANS, Das luftelektrische Potentialgefälle in Buchau a.F., Ann. Met., Hamburg, v. 3, no. 11-12, pp. 329-332, 1950 (summary in English).

KASAHARA, A., On the dynamical mechanism of the high tropospheric jet stream, Geophys. Notes, Tokyo Univ., v. 3, no. 31, 10 pp., 1950.

KRISHNASWAMY, K. R., Some characteristics of rainfall at Poona, Indian J. Met. Geophys., Delhi, v. 2, no. 1, pp. 51-56, 1951.

LEDESMA, NESTOR RENÉ, La floración del duraznero y su relación con las temperaturas de invierno y de primavera, Meteoros, Serv. Met. Nacional, Buenos Aires, no. 1, pp. 73-90, 1951 (summary in English).

LEOPOLD, LUNA B., Pleistocene climate in New Mexico, Amer. J. Sci., v. 249, pp. 152-168, 1951.

LOVERA, G., Sull'andamento annuo della pressione atmosferica in relazione con l'altezza sul maer, Proc. First Internat. Meeting on Alpine Met., Ist. Geofis. Italiano, Milano, pp. 138-140, 1950 (summary in English).

MALURKAR, S. L., Notes on analysis of weather of India and neighborhood, Memoirs, India Met. Dept., v. 28, pt. 4, pp. 139-215, 1950.

MALURKAR, S. L., Surface wet-bulb potential temperatures in and near India -- Normal values and a study in disturbed weather, Indian J. Met. Geophys., Delhi, v. 2, no. 1, pp. 25-40, 1951.

MASUDA, Y., Dynamics of baroclinic disturbances in the upper troposphere, Papers in Met. Geophys., Met. Res. Inst., Tokyo, v. 1, no. 2-4, pp. 188-197, 1950.

MATSUMOTO, S., A proposition on the advection problem, Papers in Met. Geophys., Met. Res. Inst., Tokyo, v. 1, no. 2-4, pp. 211-216, 1950.

MÖRIKOFER, W., Zur Bioklimatologie des Hochgebirges, Medizin-Meteorologische Hefte, Hamburg, No. 4, p. 10, 1950.

MÜLDNER, VILLIBRORD, Die Windbruchschäden des 22.7.1948 im Reichswald bei Nürnberg, ein Beispiel für ein Wirbelfeld als Teilerscheinung einer Böenfront, Ber. Deutsch. Wetterdienst, U.S. Zone, no. 19, Bad Kissingen, pp. 3-29, 1950.

NATIONAL REPORTS of 16 national committees to the International Association of Meteorology, I.U.G.G., Oslo, August 1948, Procès Verbeaux III, Assn. Met., I.U.G.G., 231 pp., 1950.

OGURA, Y., On the heat transfer in the lower layer of the atmosphere, Geophys. Notes, Tokyo Univ., v. 3, no. 27, 8 pp., 1950.

RODEWALD, MARTIN, Die Verwendung monatlicher Druckanomalie-Änderungskarten zu langfristigen Zirkulations-Prognosen, Ann. Met., Hamburg, v. 3, no. 11-12, pp. 361-367, 1950 (summary in English).

RODEWALD, MARTIN, Klima und Wetter der Fischereigebiete Island, Met. Amt für Nordwestdeutschland, Hamburg, 95 pp., 1951.

ROEDIGER, GEERT, Wetterskizze Nr. 8: Verbreitete Gewitterbildung durch Warmlufteinschub über Nordwestdeutschland am 3. Juli 1950, Ann. Met., Hamburg, v. 3, no. 11-12, pp. 370-374, 1950.

RONNE ANTARCTIC RESEARCH EXPEDITION, Microseisms and weather on Palmer Land Peninsula, Antarctica, Tech. Rep. 11, Office of Naval Research, 87 pp., 1950.

SANUKI, M., Studies on biplane wind vanes, ventilator tubes and cup anemometers, pt. 2, Papers in Met. Geophys., Met. Res. Inst., Tokyo, v. 1, no. 2-4, pp. 227-298, 1950.

SARMA, V. VITTAL, Comparison of geostrophic winds on constant pressure surfaces with observed winds in India, Indian J. Met. Geophys., Delhi, v. 2, no. 1, pp. 41-47, 1951.

SASAKI, Y., On the trajectory of the inertia motion of a parcel of air, Geophys. Notes, Tokyo Univ., v. 3, no. 32, 1950.

SCHULTZE, R., Über "Wetter und Krankheit" vom Standpunkt des Meteorologen, Medizin-Meteorologische Hefte, Hamburg, no. 4, pp. 6-10, 1950.

SCHWERDTFEGER, WERNER, Bases para el pronóstico a medio plazo de las condiciones de temperatura en el otoño de Buenos Aires, Meteoros, Serv. Met. Nacional, Buenos Aires, no. 1, pp. 33-45, 1951 (summary in English).

SCHWERDTFEGER, WERNER, Pequeño aporte para el conocimiento de las condiciones aerológicas en el sur de la Patagonia, An. Soc. Cient. Argentina, v. 151, pp. 57-70, 1951 (summary in English).

STRIFFLING, M., Étude synoptique des précipitations alpines, Proc. First Internat. Meeting on Alpine Met., Ist. Geofis. Italiano, Milano, pp. 50-55, 1950 (summary in English).

TAKEUCHI, M., On H. Wild's hypothesis in the theory of foehn phenomena, Papers in Met. Geophys., Met. Res. Inst., Tokyo, v. 1, no. 2-4, pp. 206-210, 1950.

UNITED STATES WEATHER BUREAU, Analysis of winds over Lake Okeechobee during tropical storm of August 26-27, 1949, Hydrometeorological Rep. 26, Washington, 11 pp. + 68 pl., 1951.

VANDENPLAS, A., Comparaison des températures minima sous abri et des températures minima au voisinage immédiat du sol en vue de la prévision des gelées au sol pendant la période de la récolte des betteraves sucrières, Inst. R. Mét. de Belgique, v. 41, 26 pp., 1951.

VANNI, M., Proposte per lo sviluppo della rete meteorologica nelle Alpi Occidentali, Proc. First Internat. Meeting on Alpine Met., Lst. Geofis. Italiano. Milano, pp. 154-157, 1950 (summary in English).

VENKITESHWARAN, S. P., The calibration equipment for the F-type radiosonde, Sci. Notes, India Met. Dept., Delhi, v. 11, no. 134, pp. 21-38 + 11 pl., 1950.

VISHER, STEPHEN SARGENT, Climatic influences, in Geography in the Twentieth Century, Griffith Taylor (ed.), pp. 196-220, 1951.

BIBLIOGRAPHY: TERRESTRIAL MAGNETISM AND ELECTRICITY

APPLETON, E., Studies of the F_2 layer in the ionosphere; I. The position of the ionospheric equator in the F_2 layer, J. Atmos. Terr. Phys., v. 1, no. 2, pp. 106-113, 1950 [abstr. in Phys. Abstr., v. 54, no. 639, p. 254, 1951].

ARGENCE, E., and Others, Contribution à l'étude de la distribution électronique de l'ionosphère et de l'absorption des ondes courtes, Ann. Géophys., v. 6, pp. 242-285, 1950 (summary in English).

BARRÉ, M., and K. RAWER, Une perturbation ionosphérique extraordinaire observée en Terre Adélie, An. Géophys., v. 6, pp. 309-317, 1950 (summary in English).

BARTELS, J., Zur Morphologie geophysikalischer Zeitfunktionen, Neue Mit., Misc. Acad. Berolinensia, pp. 69-81, 1950.

BATES, D. R., The Earth's upper atmosphere, R. Astr. Soc., Mon. Not., v. 109, pp. 215-245, 1949.

BRUCKSHAW, J. McG., and B. S. RAO, Magnetic hysteresis of igneous rocks, Proc. Phys. Soc., London, Ser. B, v. 63, pp. 931-938, 1950 [abstr. in Phys. Abstr., v. 54, no. 638, p. 172, 1951].

BRUGARD, J., and A. KASTLER, Polarisation des radiations monochromatiques du ciel nocturne et de la raie D crépusculaire, An. Géophys., v. 6, pp. 286-299, 1950 (summary in English).

COOK, K. L., Quantitative interpretation of vertical magnetic anomalies over veins, Geophysics, v. 15, pp. 667-686, 1950 [abstr. in Phys. Abstr., v. 54, no. 638, p. 172, 1951, and in Geophys. Abstr., p. 245, 1950.

de ANDRADE, ADALBERTO, and Others, Minas de ferro de Montemór-o-Novo, Portugal, Servico de fomento mineiro, Relatoria, no. 15, 125 pp., 1949 [abstr. in Geophys. Abstr., p. 180, 1950].

de SITTER, L. U., Eindverslag van het geophysiche onderzoek in ZO-Nederland (Geophysical survey of the southeast Netherlands), Med. Geol. Stichtung, Ser. C, v. 1, pt. 3, no. 1, 372 pp., 1949 (condensed translation in English) [abstr. in Geophys. Abstr., p. 179, 1950].

DUFAY, J. and M., Étude du spectre du ciel nocturne, de 6800 à 9000 A, C.-R. Acad. Sci., Paris, v. 232, pp. 426-428, 1951.

ELSASSER, WALTER M., Boundary-value problems of hydromagnetics, Off. Naval Res. (416:COA:mls NR-081-068; Ser. 10371; 5/5/50), pt. 1, 37 pp., September 1950 (processed).

ERRULAT, F., Zur Frage der lokalen und regionalen Anomalien der Säkularvariation, Deut. Hydrogr. Zs., v. 3, pp. 153-161, 1950.

FRANCE, BUREAU DES RECHERCHES GÉOLOGIQUES ET GÉOPHYSIQUES, Prospection électrotellurique de la Bresse et du Bas-Dauphiné, Pub. 5, 47 pp., 1948 [abstr. in Geophys. Abstr., p. 188, 1950].

FRITSCH, V., Blitzschläge im Gebirge, Proc. First Internat. Meeting on Alpine Met., Ist. Geofis. Italiano, Milano, pp. 119-123, 1950 (summary in English).

GAUZIT, J., The light of the night sky, and its origin, Scientia, v. 85, pp. 267-271, 1950 (in French) [abstr. in Phys. Abstr., v. 54, p. 175, 1951].

GILL, P. S., Lead absorption of cosmic rays at different altitudes near magnetic latitude 22°N, Nature, v. 166, pp. 318-319, 1950.

HAALCK, H., Prinzip und Theorie einer für besondere Aufgaben der praktischen Geophysik zweckmässigen Feldwaagenkombination, Gerlands Beitr. Geophys., v. 61, pp. 235-239, 1950 (Measures vertical gradient of horizontal intensity).

HURLEY, P. M , and J. B. THOMPSON, Airborne magnetometer and geological reconnaissance survey in northwestern Maine, Geol. Soc. Amer. Bull., v. 61, pp. 835-842, 1950 [abstr. in Geophys. Abstr., p. 181, 1950].

ISHIKAWA, G., On the initial phase of geomagnetic storm, Papers in Met. Geophys., Met. Res. Inst., Tokyo, v. 1, no. 2-4, pp. 319-336, 1950.

JACKSON, W., "Sudden commencements" in geomagnetism, Letter in Nature, London, v. 166, pp. 691-692, 1950 [abstr. in Phys. Abstr., v. 54, no. 638, p. 172, 1951].

MATSUSHITA, S., Circulatory motions in the ionospheric atmosphere and their relation to the S field of terrestrial magnetism, J. Geomag. Geoelect., v. 2, pp. 9-19, 1950.

MEYER, O., Ergebnisse der erdmagnetischen Messungen im nordwestdeutschen Raum 1948 zur Erfassung der Säkularvariation, Deut. Hydrogr. Zs., v. 3, pp. 161-162, 1950.

MISAKI, M., A method of measuring the ion spectrum, Papers in Met. Geophys., Met. Res. Inst., Tokyo, v. 1, no. 2-4, pp. 313-318, 1950.

MODRINIAK, N., Geophysical investigation of Rotorua, New Zealand J. Sci. Technol., v. 30, pp. 1-19, 1949 [abstr. in Geophys. Abstr., p. 180, 1950].
NICOLET, M., Propositions pour une nomenclature de la haute atmosphère, An. Géophys., v. 6, pp. 318-321, 1950.
PAUL, BERNT, Geoelektrische Schlumberger Messungen an der Erdoberfläche und in Bohrloch, Erdöl und Tektonik in Nordwestdeutschland, pp. 302-307, 1949 [abstr. in Geophys. Abstr., p. 185, 1950].
POISSON, CHARLES, Le magnétisme terrestre à Madagascar, Acad. Malgache, Mém., fasc. 37, 83 pp., 1949 [abstr. in Geophys. Abstr., p. 154, 1950].
POLDINI, E., Interprétation tectonique des variations du champ tellurique, Schweizer Vereinigung Pet.-Geologen u. Ing., Bull., v. 17, no. 52, pp. 1-4, 1950 [abstr. in Geophys. Abstr., p. 168, 1950].
PONTIER, L., Amplitude de la variation diurne de H au voisinage de l'équateur magnétique au Togo, An. Géophys., v. 6, pp. 238-241, 1950.
RAJA RAO, K. S., The geomagnetic equator, Current Science, Bangalore, v. 18, pp. 120-123, 1949.
RAWER, K., Geometrical optics of ionospheric propagation, Nature, v. 166, p. 316, 1950.
RIKITAKE, T., Electromagnetic induction within the Earth and its relation to the electrical state of the Earth's interior, pt. 1, Bull. Earthquake Res. Inst., Tokyo Univ., v. 28, pt. 1-2, pp. 45-100, 1950 (deals only with geomagnetic transients).
ROCHE, ALEXANDRE, Anomalies magnétiques accompagnant les massifs de pépérites de la Limagne d'Auvergne, C.-R. Acad. Sci., Paris, v. 230, pp. 1603-1604, 1950 [abstr. in Geophys. Abstr., p. 155, 1950].
ROQUET, J., Sur l'aimantation rémanente isotherme de la magnétite en grains fins dispersés, C.-R. Acad. Sci., Paris, v. 232, pp. 946-948, 1951.
ROUGERIE, PAUL, Variation diurne lunaire de la déclinaison magnétique et de la composante verticale du champ terrestre au Val-Joyeux, An. Géophys., v. 6, pp. 300-308, 1950 (abstract in English).
TERADA, K., Electromagnetic induction within the Earth's crust of variable conductivity, pt. 2, Geophys. Mag., v. 16, no. 1, pp. 5-56, 1948.
TSUBOKAWA, IETSUNE, General description of a new type magnetometer (the GSB type magnetometer), Bull. Geogr. Surv. Bur., Geophys. Sup. no. 1, Japan, 6 pp. + 2 pl., 1949.
TSUBOKAWA, I., A new type magnetometer, Bull. Geogr. Surv. Inst., Japan, v. 2, pt. 1, pp. 73-76, 1950.
TSUBOKAWA, I., and Others, Magnetic survey in the southwestern part of Japan, Bull. Geogr. Surv. Inst., Japan, v. 2, pt. 1, pp. 77-79, 1950.
WEBER, E. K., and Others, Die magnetische Anomalie westlich von Locarno, Schweizer. min. pet. Mitt., v. 29, pp. 492-509, 1949 [abstr. in Geophys. Abstr., p. 155, 1950].
WEICKMANN, H. K., and H. J. AUFM KAMPE, Preliminary experimental results concerning charge generation in thunderstorms concurrent with the formation of hailstones, J. Met., v. 7, pp. 404-405, 1950.

BIBLIOGRAPHY: OCEANOGRAPHY

ALLEN, J., Tidal sand ripples, Dock Harb. Auth., v. 31, p. 348, 1951.
ANONYMOUS, Circulation of water in the oceans, Nature, v. 167, pp. 543-545, 1951.
ARRHENIUS, OLOF, Three sediment cores from the Tyrrhenian Sea; IV, The phosphate content of some sediments from the Mediterranean, Göteborgs Kgl. Vetenskaps- Vitterhets-Samhdäll Handl., v. 6, Ser. B5, no. 13, pp. 26-29, 1948 [abstr. in Chem. Abstr., v. 45, p. 86, 1951].
BANAL, ..., Le mascaret en Seine: historique description et mesure du phénomène, théorie, Mém. Trav. Soc. Hydrotech. France, Houille Blanche, v. 5, p. 134, 1950.
BIESEL, F., Calculation of wave damping in a viscous liquid of known depth, Houille Blanche, v. 4, pp. 630-634, Sept.-Oct. 1949 (in French) [abstr. in Appl. Mech. Rev., v. 3, no. 12, p. 397, 1950].
CARRUTHERS, J. N., and Others, Studies of water movements and winds at various lightvessels; II, At the Seven Stones Lightvessel near the Scilly Isles, J. Mar. Biol. Assn., v. 29, pp. 587-608 + 4 pl., 1951.
DUNBAR, M. J., Eastern Arctic waters, Fish. Res. Bd. Canada Bull. no. 88, 131 pp., Ottawa, 1951.
EMERY, K. O., and ROGER REVELLE, Large floating islands of the Arctic Ocean, Bull. Geol. Soc. Amer., v. 62, p. 325, 1951.
FLETCHER, J. O., Floating ice islands in the Arctic Ocean, Tellus, v. 2, pp. 323-324, 1950.
FRIEDRICH, HERMANN, Versuch einer Darstellung der relativen Besiedlungsdichte in den Oberflächenschichten des Atlantischen Ozeans, Kieler Meeresforschungen, v. 7, pp. 108-121, 1950.
GREAT BRITAIN, National Institute of Oceanography, Annual Report 1949-50, 48 pp., Cambridge, 1951.

HIDAKA, KOJI, Wind-driven currents and surface contours in an enclosed ocean, and the lateral mixing, Geophys. Notes, Tokyo Univ., v. 3, no. 12, 16 pp., 1950.
HIDAKA, KOJI, Eigenvalue problem in relation to the lateral mixing, Geophys. Notes, Tokyo Univ., v. 3, no. 11, 3 pp., 1950.
HIDAKA, KOJI, Circulation in a zonal ocean induced by a planetary wind system, Geophys. Notes, Tokyo Univ., v. 3, no. 10, 8 pp., 1950.
HIDAKA, KOJI, Drift currents in an enclosed ocean, pt. 1, Geophys. Notes, Tokyo Univ., v. 3, no. 23, 23 pp., 1950.
JUNE, FRED C., Notes on the tuna and bait resources of the Hawaiian, Leeward, and Line Islands, Comml. Fisher. Rev., v. 13, no. 1, pp. 1-22, 1951.
KALLE, KURT, Die natürlicher Eigenschaften der Gewässer, Handb. Seefischerei Nordeuropas, v. 1, no. 2, 37 pp., 1949.
KALLE, KURT, Die waagerechte Gliederung und die Tiefen des Meeres, Handb. Seefischerei Nordeuropas, v. 1, no. 1, 23 pp., 1949.
KENNARD, E. H., Generation of surface waves by a moving partition, Q. Appl. Math., v. 7, pp. 303-312, 1949 [abstr. in Appl. Mech. Rev., v. 4, no. 1, p. 15, 1951].
KEULEGAN, GARBIS H., Wind tides in small closed channels, J. Res. Nat. Bur. Stand., v. 46, pp. 358-381, 1951.
MIELCHE, H., and A. F. BRUUN, Science and the man in the street; a deep-sea expedition around the world, Danish For. Of. J., no. 3, pp. 14-18, 1950.
MUKHERJEE, S. M., Microseisms and sea waves, Bull. Seis. Soc. Amer., v. 41, pp. 1-4, 1951.
NETHERLANDS, Konink. Nederl. Meteor. Inst., Zeegebieden rond Australie; oceanografische en meteorologische gegevens, The Hague, no. 124, 96 pp., 1949.
ÖSTMAN, C. J., Om sambandet mellan köldsummor islaggning och istjocklek, Med. Swedish Met. Hydrolog. Inst., Ser. A, no. 1, 20 pp., 1950 (summary in English).
OWEN, DAVID M., Deep-sea underwater photography and some recent stereoscopic applications, Photogramm. Eng., v. 17, pp. 13-19, 1951.
PETERS, A. S., The effect of a floating mat on water waves, Comm. Pure Appl. Math., v. 3, pp. 319-354, 1950.
POLLI, SILVIO, Costanti armoniche e non armoniche delle maree di cuattro località della Laguna di Venezia (Paliaga, Torcello, Torson di Sotto, Millecampi), Archiv. Ocean. Limnol., v. 7, pp. 17-27, 1950 (summary in German).
POLLI, SILVIO, Penetrazione delle radiazioni luminose nel ghiaccio e nella neve, Ann. Geofis., v. 3, no. 3, 7 pp., 1950.
PRATJE, OTTO, Die Bodenbedeckung der nordeuropäischen Meere, Handb. Seefischerei Nordeuropas, v. 1, no. 3, 23 pp. + 3 charts, 1949.
RIIS-CARSTENSEN, EGIL, Farvandene omkring Grönland, Grönlands Bogen, Copenhagen, v. 1, pp. 63-84, 1950.
REVELLE, ROGER, 1940 E. W. Scripps cruise to the Gulf of California; sedimentation and oceanography: survey of field operations, Geol. Soc. Amer. Mem. 43, pt. 5, 6 pp., 1950.
RODEWALD, MARTIN, Einige Bemerkungen zur Wassertemperatur vor dem Westausgang der Biskaya, Ann. Met., v. 3, pp. 303-312, 1950 (summary in English).
SHEPARD, F. P., Submarine topography of the Gulf of California, Geol. Soc. Amer. Mem. 43, pt. 3, vii + 32 pp. + 11 charts, 1950.
STOMMEL, HENRY, An elementary explanation of why ocean currents are strongest in the west, Bull. Amer. Met. Soc., v. 32, pp. 21-23, 1951.
STOMMEL, HENRY, Streaks on natural water surfaces, Weather, v. 6, pp. 72-74, 1951.
SVERDRUP, H. U., Physical oceanography of the North Polar Sea, Arctic, v. 3, pp. 178-186, 1950.
U. S. HYDROGRAPHIC OFFICE, Techniques for forecasting wind waves and swell, H.O. Pub. 604, 37 pp., 1951.
VALEMBOIS, J., Étude d'un appareil permettant la reproduction de l'onde marée dans un modèle d'estuaire, Mém. Trav. Soc. Hydrotech. France, Houille Blanche, v. 5, no. 2, pp. 150-154, 1950 (summary in English, p. 111).
VERCELLI, FRANCESCO, Trasparenza e colore delle acque della laguna di Venezia, Archiv. Ocean. Limnol., v. 7, pp. 3-14, 1950.
WEIDEMANN, HARTWIG, Untersuchungen über unperiodische und periodische hydrographische Vorgänge in der Beltsee, Kieler Meeresforschungen, v. 7, pp. 70-86, 1950.
WEISSLER, ALFRED, and V. A. DEL GROSSO, The velocity of sound in sea water, J. Acoustical Soc. Amer., v. 23, pp. 219-223, 1951.
WUEST, WALTER, Contribution to the generation of water waves by wind, Zs. Angew. Math. Mech., v. 29, pp. 239-252, 1949 (in German) [abstr. in Appl. Mech. Rev., v. 3, no. 12, p. 433, 1950].
WYRTKI, KLAUS, Über die Beziehungen zwischen Trübung und ozeanographischem Aufbau, Kieler Meeresforschungen, v. 7, pp. 87-107, 1950.

BIBLIOGRAPHY: VOLCANOLOGY

ANDREATTA, CIRO, Notizie sulla costiluzione del complesso effusivo permiano del Trentino-Alto Adigi, Rendiconti della Soc. Mineralogica Italiana, v. 6, pp. 48-53, 1950.

DE ROEVER, W. P., Preliminary notes on glaucophane-bearing and other crystalline schists from South East Celebes, and the origin of glaucophane-bearing rocks, Proc. Kon. Ned. Akad. Wet., v. 53, no. 9, pp. 1455-1465, 1950.

EPSTEIN, S., and Others, Carbonate-water isotopic temperature scale, Bull. Geol. Soc. Amer., v. 62, pp. 417-426, 1951.

FISCHER, R., Entmischungen in Schmelzen aus Schwermetalloxyden, Silikaten und lagerstättenkundliche Bedeutung, Neues Jb. Miner. Abh., v. 81, pp. 315-364, 1950.

GEORGALAS, G. C., Beiträge zur Kenntnis einiger jungtertiärer Eruptivgesteine der Insel Imbros (mit 6 Texfiguren und 7 Abbildungen in 5 Tafeln), Bull. Volcanologique, Ser. 2, v. 10, pp. 1-43 + 5 pl., 1950.

GORAI, MASAO, Method of distinguishing C-twin and A-twin of plagioclase under ordinary polarization microscope, J. Geol. Soc. Japan, v. 56, no. 660, pp. 441-443, 1950 (summary in English).

JÉREMINE, E., and G. LUCAS, Note sur quelques roches volcaniques de la Région d'Oujda (Maroc Oriental), Bull. Volcanologique, Ser. 2, v. 10, pp. 131-146 + 1 pl., 1950.

JUGOVICS, LAJOS, Daten zur Kenntnis der Andesite des Cserhát Gebirges (Ungarn), Földtani Közlöny, v. 79, pp. 447-453, 1949 (summary in German).

KATO, YOSHIO, and RIKII SHOJI, Prospecting of the underground structure of the new volcano "Showashinzan" by the seismic method, Bull. Volcanologique, Ser. 2, v. 10, p. 129 + 1 pl., 1950.

KOARK, H. J., Die Serpentinite des Ochsners (Zillertal) und des Reckners (Tarntal) als Beispeil polymetamorpher Fazies verschiedener geologischer Stellung, Neues Jb. Miner. Abh., v. 81, pp. 399-476, 1950.

KOHLER, J., Metamorphe Differentiation an einem Beispeil aus der Oberpfalz., Neues Jb. Miner. Abh., v. 81, pp. 365-398, 1950.

MERLIN, O. HIEKE, Chimismo di lave basaltiche della regione Hararino-Dancala in Africa Orientale, Rendiconti della Soc. Mineralogica Italiana, v. 6, pp. 101-112, 1950.

MINAKAMI, TAKESHI, Report on the volcanic activities in Japan during 1939-1947, Bull. Volcanologique, Ser. 2, v. 10, pp. 45-58 + 12 pl., 1950.

MINAKAMI, TAKESHI, On explosive activities of Andesitic volcanoes and their forerunning phenomena, Bull. Volcanologique, Ser. 2, v. 10, pp. 59-87 + 16 pl., 1950.

NOVITZKY, ALEXANDRO, Diccionario Minero-Metallurgico-Geologico-Mineralogico-Petrografico y de Petroleo Ingles-Español-Frances, Aleman, Ruso, Imprenta "Chile," Charcas 433, Buenos Aires, 369 pp., 1951.

PATTERSON, EDWARD M., An occurrence of quartz-trachyte among the tertiary basalt lavas of northeast Ireland, Proc. R. Irish Acad., v. 53, sec. B, no. 14, pp. 265-287, 1951.

SANDREA, A., Étude sur quelques laves de l'Île Maurice, Bull. Volcanologique, Ser. 2, v. 10, pp. 147-155 + 2 pl., 1950.

SAN MIGUEL DE LA CAMARA, MAXIMINO, Volcanes y erupciones volcánicas de España estudiados y descritos en estos últimos años, Bull. Volcanologique, Ser. 2, v. 10, pp. 89-116, 1950.

SCHERILLO, ANTONIO, Le ricerche petrografiche sui prodotti attuali del Vesuvio compiute nell' istituto di Mineralogia dell'Universita di Napoli, Bull. Volcanologique, Ser. 2, v. 10, pp. 117-124, 1950.

SCHIAVINATO, G., Limburgite e basalti limburgitici della Provincia Magmatica euganeobericolessinea, Rendiconti della Soc. Mineralogica Italiana, v. 6, pp. 135-155, 1950.

TANEDA, S., Petrological discussion on magnetite (II), J. Geol. Soc. Japan, v. 56, no. 660, pp. 415-422, 1950 (summary in English).

THORARINSSON, SIGURDUR, The eruption of Mt. Hekla 1947-1948, Bull. Volcanologique, Ser. 2, v. 10, pp. 157-168 + 18 pl., 1950.

TYRRELL, G. W., The Tertiary igneous rocks of Scotland in relation to Iceland and Greenland, Med. Dansk Geol. Forening, v. 11, no. 4, pp. 413-440, 1949.

van der WAALS, LUCAS, De Geologie Vaneengebied Tennoorden van la Spezia (zuid-oost Liguria-Italie), Proefschrift Thesis, 1946, Geol. Inst., Amsterdam, 92 pp., 1950.

WAHL, W. G., and F. FITZ OSBORNE, Cawatose Map-Area, Geol. Rep. 44, Dept. Mines, Geol. Survey Branch, Prov. Quebec, Canada, 37 pp., 1950.

BIBLIOGRAPHY: HYDROLOGY

AHMAD, MUSHTAG, Spacing and projection of spurs for bank protection, Civ. Eng., Public Works Rev., v. 46, no. 537, pp. 172-174, 1951.

ARKELL, W. J., The structure of Spring Bottom Ridge, and the origin of the Mud-slides, Osmington, Dorset, Proc. Geol. Assn., v. 62, pt. 1, pp. 21-30, 1951.
ARNOLD, JAMES S., An electromagnetic flow meter for transient flow studies, Rev. Sci. Inst., v. 22, pp. 43-47, 1951.
BAMBER, H. A., The hydrology of the Lathkill Dale area of Derbyshire, Cave Sci., no. 15, pp. 293-304, 1951.
BANERJEE, S. K., Off-season flood in the river Mayurakshi in May 1949, J. Cent. Bd. Irrig., v. 7, pp. 315-322, 1950.
BLENCH, T., Anomalous behavior of wells in water-logged areas, Houille Blanche, v. 6, no. 1, p. 11, 1951.
BOURCART, J., Glanes morphologiques, Rev. Géomorph. Dyn., v. 2, no. 1, pp. 36-38, 1951.
BRUTTIN, J. F., L'aménagement hydroélectrique de Rossens-Hauterive après deux ans d'expérience, Bull. Tech. Suisse Romande, v. 77, no. 6, pp. 69-85, 1951.
CHAMAYOU, H., Recherche d'une loi périodique sur l'hydraulicité, Houille Blanche, v. 5, pp. 529-534, 1950.
CHARLES, JOHN R., Occurrence, development, and use of underground water, Water Works Eng., v. 104, pp. 219-220, 1951.
CHEBOTAREV, N. P., Evaporation from the surface of soil when the level of ground waters is below the surface, Dok. Ak. Nauk., SSSR, v. 71, no. 2, pp. 275-276, 1950.
CROKER, G. N., Records of flows in the river Wye system, as determined by current-meter measurements, with a note on flood warning arrangements, J. Inst. Water Eng., v. 5, pp. 39-97, 1951.
CROSS, WILLIAM P., and EARL E. WEBBER, Ohio stream-flow characteristics, pt. 2, Water supply and storage requirements, Ohio Dep. Nat. Res., Div. of Water, Columbus, Bull. 13, 13 pp., 181 fig., 1950.
de BOER, H. J., On the relation between rainfall and altitude in Java, Indonesia, Chronica Naturae, v. 106, pp. 424-427, 1950.
FIDMAN, B. A., Some experimental data on large-scale turbulence in open flow, Inst. Geogr. Acad. Sci., USSR, 13 pp., 1950.
FIX, PHILIP F., and Others, Ground water in the Escalante Valley, Beaver, Iron, and Washington Counties, Utah, Utah Tech. Pub. 6, 210 pp., 1950.
FRIEDRICH, WILHEM, Periodische und unperiodische Schwankungen des Abflusses, Sonderheft, Die Wasserwirtschaft, pp. 14-20, 1950.
GAGE, MAXWELL, Stream patterns in the Greymouth district, Trans. Proc. R. Soc. New Zealand, v. 78, pt. 4, pp. 418-425, 1950.
GOINES, W. H., and Others, Water supply of the Houston Gulf Coast region, Texas Bd. Water Eng., Bull. 5101, 16 pp. + 22 fig., 1951.
HARBECK, G. EARL, JR., and Others, Utility of selected western lakes and reservoirs for water-loss studies, Geol. Sur. Circ. 103, 31 pp., 1951.
HEARTZ, R. E., The development of the St. Maurice River, Houille Blanche, v. 6, pp. 46-48, 1951.
HYLAND, W. L., and REECE, G. M., Water supplies for army bases in Alaska, J. New England Water Works Assn., v. 65, pp. 1-16, 1951.
ISMAIL, HASSAN M., Turbulent transfer mechanism and suspended sediment in closed channels, Proc. Amer. Soc. Civ. Eng., v. 77, separate 56, 26 pp., 1951.
JOHNSON, F. A., Some reservoir sites in the Sierra Nevada, California, Geol. Sur. Circ. 85, 28 pp., Dec. 1950.
JONES, J. H., and Others, A variable reference technique for analysis by absorption spectrophotometry; I. Theory and discussion, II. Practical applications, J. Assn. Off. Agri. Chem., v. 34, pp. 135-179, 1951.
KLAER, F. H., JR., and Others, Ground-water resources of the Columbus area, Bartholomew County, Indiana, Ind. Dep. Cons., Div. of Water Resources, 37 pp., 1951.
KUENEN, PH. H., Mechanics of varve formation and the action of turbidity currents, Geol. Föreningens Förhandlingar, v. 73, no. 464, pp. 69-84, 1951.
LÁSZLÓFFY, W., Velocity computations in open channels, Vizügyi Közlemények, no. 1-2, pp. 3-69, 1950 (in Hungarian with Russian, French, and German summaries).
LINTON, DAVID L., Midland drainage; some considerations bearing on its origin, Advancement of Science, v. 7, no. 28, pp. 449-456, 1951.
MENSCHING, H., Akkumulation und Erosion Niedersächsischer Flüsse seit der Risseiszeit, Erdkunde, v. 5, no. 1, pp. 60-70, 1951.
MOOKERJEE, D., Estimation of runoff in the design of cross-drainage works, J. Cent. Bd. Irrig., v. 7, pp. 306-308, 1950.
REMENIERAS, GASTON, and JEAN BOYER, Monographie hydrologique du bassin de la Maronne, pt. 3, Houille Blanche, v. 5, pp. 788-790, 1950.
ROY, DIPAK KUMAR, The River Meanders, J. Geol. Inst., Presidency College, Calcutta, v. 12, no. 1, pp. 55-58, 1949-50.

SCHIFFERS, H., Wasserhaushalt und probleme der Wassernutzung in der Sahara, Erdkunde, v. 5, pp. 51-60, 1951.
SCHOFF, STUART L., and EDWIN W. REED, Ground water in alluvial deposits in Oklahoma, Econ. Geol., v. 46, no. 1, pp. 76-83, 1951.
SHIMOZURU, D., Change of the ground-water level due to the Imaichi Earthquake, Bull. Earthquake Res. Inst., v. 28, pp. 129-132, 1950.
STEVENS, GUY C., and CLAYTON H. HARDISON, Monthly and annual discharge of Missouri River between Fort Benton, Mont., and Hermann, Mo., and principal tributaries, Geol. Sur. Circ. 108, 37 pp., 1951.
STRETTA, E., Hydrogéologie du flanc nord des Beni Snassen en amont de Berkane, Notes Serv. Géol., v. 2, no. 74, pp. 213-221, 1950.
TAYLOR, J. H., The contribution of petrology to the study of sedimentation, Science Progress, v. 38, no. 152, pp. 652-667, 1950.
THIRION, CH., Etude sur le pouvoir feltrant des sols par la méthode A. Muntz améliorée, dans le périmètre de l'avant-project du canal d'irrigation de Trèbes à Lézignan-Corbières (Aude), Génie Civil, v. 127, no. 19, pp. 367-370, 1950.
TROXELL, H. C., and Others, Some aspects of the water supply in the South Coastal Basin, Calif., Geol. Sur. Circ. 105, 10 pp., 1951.
VENKATARAMANAN, K., Artesian wells, J. Cent. Bd. Irrig., v. 7, pp. 303-305, 1950.
VERIGIN, N. N., Ground-water flow in the case of local intensified infiltration, Dok. Ak. Nauk, SSSR, v. 70, no. 5, pp. 777-779, Feb. 11, 1950.

BIBLIOGRAPHY: TECTONOPHYSICS

ALMELA, D. A., and JOSÉ MA. D. RÍOS, Mapa Geol. España, Alquezar, Inst. Geol. Min. España, no. 130, 58 pp., 1950.
ARKELL, W. J., The structure of Spring Bottom Ridge and the origin of the mud-slides, Osmington Dorset, Proc. Geol. Assn., v. 62, pp. 21-30, 1951.
BÉLAND, RENÉ, Le synclinal du lac Wakeham et la fosse du Labrador, Naturaliste Canadien, v. 77, pp. 291-304, 1950.
BIRCH, FRANCIS, A simple technique for the study of the elasticity of crystals, Amer. Min., v. 35, pp. 644-650, 1950.
BLUMENTHAL, M. M., Beiträge zur Geologie des Landschaften am Mittleren und Unteren Yeşil Irmak (Tokat, Amasya, Havza, Erbaa, Niksar), Maden Tetkik ve Arama Enstitüsü, Geol. harta, Ankara, ser. D, no. 4, 153 pp., 1950.
CORNELIUS, HANS PETER, Zur Selbstverzerrung der Faltenzüge im Gefolge der Orogenese, SitzBer., pt. 1, 158B, no. 5, pp. 337-373, 1949.
de CIZANCOURT H., Deep tectonics and isostasy, J. Geol., v. 59, pp. 39-59, 1951.
DUBOURDIEN, G., and G. DUROZO, Observations tectoniques dans les environs de Tébessa et de l'Quenza (Algérie), Bull. Soc. Géol. France, 5 ser., v. 20, pp. 257-266, 1950.
FALLOT, P., Remarques sur la tectonique de couverture dans les Alpes bergamasques et les Dolomites, Bull. Soc. Géol. France, 5 ser., v. 20, pp. 183-195, 1950.
GEUKENS, FERNAND, Contribution à l'étude de la partie Nord-Ouest du massif Cambrien de Stavelot, Mém. Inst. Géol. Univ. Louvain, v. 16, no. 11, 170 pp., 1950.
GOGUEL, JEAN, La racine de la nappe du Guil et l'eventail briancannais, Bull. Soc. Géol. France, 5 ser., v. 20, pp. 289-296, 1950.
GUZIK, KAZIMIERZ, and WLADYSLAW POZARYSKI, Biecz anticline (middle Carpathians), Inst. Géol. Pologne, Warsaw, Bull. 53, 32 pp. + 1 pl., 1949 (in Polish with summary in English).
HEISKANEN, W., On the isostatic structure of the Earth's crust, Ann. Acad. Sci. Fennicae, ser. A3, Geol. Geogr., v. 22, pp. 1-60, 1950.
HERNANDEZ-PACHECO, F., Síntesis geomarfológica del país vasco en los limites de Guipúzcoa y Navarro, Bol. real Soc. Española, Hist. Nat., Sec. Geol., v. 48, pp. 5-23, 1950.
HILGENBERG, OTT CHRISTOPH, Die Bruch Struktur der siallischen Erdkruste, Akademie-Verlag, Berlin, 106 pp., 1949.
HILL, R., The mathematical theory of plasticity, Clarendon Press, Oxford, 354 pp., 1950.
HUNDT, RUDOLF, Erdfalltektonik, W. Knapp, Halle, 145 pp., 1950.
IPPOLITO, F., Il Monte Pisano, Mem. Note Inst. Geol. Applicata, Univ. Napoli, v. 3, pp. 1-115, 1949-50.
KIENOW, S., Experimentelle Untersuchungen über das Festigkeitsverhalten und den Deformationsmechanismus von trockenem Ton unter verschiedenen allseitigen Drucken, Neues Jb., no. 2, pp. 39-52, 1951.
KINDELÁN, D. T. A., and Others, Mapa Geol. España, Casares, Inst. Geol. Min. España, no. 109, 62 pp., 1949.

LADURNER, JOSEF, Beiträge zur Typisierung von Quartz Falten, Tschermaks Min. Petr. Mitt., v. 2, pp. 47-66, 1950.
MASAO, GORAI, Method of distinguishing C-twin and A-twin of plagioclase under ordinary polarization microscope, J. Geol. Soc. Japan, v. 56, no. 660, pp. 441-443, 1950.
MOORHOUSE, W. W., Geology of Osway Township, Ont. Dept. Mines An. Rep. 58 (1949), pt. 5, 27 pp., 1951.
NAKAYAMA, ISAMU, Petrofabric study of the Oboke phyllitic sandstone, J. Geol. Soc. Japan, v. 56, no. 660, pp. 433-438, 1950.
REINER, MARKUS, Deformation and flow, Lewis and Co., London, 346 pp., 1949.
ROSO de LUNA, D. I., and D. F. HERNÁNDEZ-PACHECO, Mapa Geol. España, Mirandilla, Inst. Geol. Min. España, no. 125, 91 pp., 1949.
SCHMID, E., and W. BOAS, Plasticity of crystals, Hughes and Co., London, 353 pp., 1950.
SONDER, R. A., Gefügeregelung, Druckschieferung und Druckverformung von Gesteinen, Schweiz. Min. Petr. Mitt., v. 28, no. 1, pp. 363-379, 1950.
STEVENS, N. C., The geology of the Canowindra District, N.S.W., J. Proc. R. Soc. New South Wales, v. 82, pt. 4, pp. 319-337, 1950.
ŚWIDZIŃSKI, HENRYK, Stróże scale near Grybów (Middle Carpathians), Inst. Géol. Pologne, Warsaw, Bull. 59, 70 pp. + 6 pl., 1950 (in Polish with summary in English).
TERTSCH, H., Die Festigkeit der Scheinungen der Kristalle, Springer, Wien, 310 pp., 1949.
VITAPLANA, F. R., La estructura de la península Iberia y sus relaciones con Europa, América y Africa, Rev. Obras Públicas, Madrid, pp. 1-18, 1950.
von GAERTNER, HANS RUDOLF, Probleme des Saxothüringikums, Geol. Jb., v. 65, pp. 409-450, 1950.
WALLACE, ROBERT E., Geometry of shearing stress and relation to faulting, J. Geol., v. 59, no. 2, pp. 118-130, 1951.

NOTES AND PERSONALIA

NOTES (including Corrigenda)

Corrigenda--In the February 1951 issue, the last sentence of the only full paragraph of the Harrington paper on page 79 should read "However, variations in the relative sizes of the quadrilaterals reduce the indices to a qualitative value." The word "quantitative" is incorrect.

In the April 1951 issue, the latter part of the second line of the second full paragraph of the Howell paper on page 182 should read ". . . originates above the turbulent layer and later enters . . ." The second "layer" as printed is incorrect.

Also in the April 1951 issue, the fifth full paragraph of the Roberts report on page 280 should open "The development, by the Naval Ordnance Laboratory, of a new . . ." The parenthetic "with the cooperation of the Naval Ordnance Laboratory" is incorrect.

On the first page of the Program of the Annual Meeting, page 305, the Committee on Meetings given is the Committee for the previous triennium. The Committee now consists of John Putnam Marble (Chairman), Woodrow C. Jacobs, Herbert S. Riesbol, Walter E. A. Ruska, Glenn E. Stout, and Frank J. Veihmeyer.

Fellowship Program of the Shell Oil Company--Announcement has been made of the expanded Shell Fellowship Program for 1951-52. This involves 12 Fundamental Research Grants of $5000 each established in various universities, and 45 fellowships totaling $75,000 for graduate study in various fields of physical research including geophysics. Interested persons should write to the Shell Fellowship Committee, 50 W. 50th St., New York 20, N. Y.

Civil Service examinations for junior scientists and engineers--The U. S. Civil Service Commission has announced an unassembled examination for junior scientists and engineers in Grades GS-5 and GS-7 ($3100 to $3825 per year), involving various branches. The examination is to be used in filling vacancies in the Washington, D. C., area and has indicated no closing date. Interested persons should secure Announcement 276 of the Commission from postoffices or directly from the Civil Service Commission, Washington 25, D. C.

Civil Service examination for geologists--Announcement 287 of the U. S. Civil Service Commission dated April 17, 1951, concerns examinations for geologists in Grades GS-9 to GS-13 ($4600 to $7600 per year). Ten specialties are cited, including ground-water geology and sedimentation. No closing date was given. Interested persons should apply to the nearest postoffice or directly to the Civil Service Commission, Washington 25, D. C.

Cancellation of the meeting of the International Astronomical Union--The meeting of the International Astronomical Union, scheduled to be held in Leningrad in the summer of 1951, has been cancelled.

Reprint of the first edition of Darwin's Origin of Species--The Philosophical Library, New York 16, N. Y., has issued a reprint of the first edition of Darwin's Origin of Species, first published in 1859. As the book came under criticism, later editions were expurgated and modified. This is the first reprinting of the first edition, reproduced as originally written, except for punctuation.

New Institute of Oceanography in Egypt--Announcement has been made of the establishment of the Alexandria Royal Institute of Oceanography as a branch of Farouk I University in Alexandria. The Mediterranean Sea will be the principal subject of study. Abdel Fattah Mohamed, Professor in the Department of Oceanography of Farouk I University, now engaged in work and study at Scripps Institution of Oceanography, has been designated as the first director.

Symposium on Hydrodynamics in Modern Technology at Massachusetts Institute of Technology--On June 4-6, the above symposium was held at the Massachusetts Institute of Technology in connection with the dedication of the new Hydrodynamics Laboratory and Ship Model Towing Tank. Twenty-five scientific papers were presented by national leaders in various aspects of hydrodynamics and related fields.

Festival at Perkins Astronomical Observatory--Ohio State University and Ohio Wesleyan University joined in a Perkins Astronomy Festival on May 3-5. Otto Struve was the principal speaker at the Annual McMillan Lecture given on May 3 in the new Physics Building of Ohio State University.

Conference on Auroral Physics--A Conference on Auroral Physics, jointly sponsored by the Physics Department of the University of Western Ontario and the Geophysical Research Directorate of the Air Force Cambridge Research Laboratories, Cambridge, Massachusetts, will be held July 23 to 26 at the University of Western Ontario at London, Ontario. General topics to be discussed will deal with the formation of the aurora, mechanisms of solar corpuscular streams, and excitation mechanisms in the ionosphere (80-400 km) and in the mesophere (400-1000 km). Important theoretical papers are to be given by internationally known scientists. Also, several papers will be presented on the identification and interpretation of the emission spectra of the ionosphere and mesosphere and other observational studies.

PERSONALIA

Theodore Arnow of the Mineola, N. Y., office of the Ground-Water Branch of the U. S. Geological Survey, is now on a special assignment on the Navy's water-supply problems of the islands of the Trust Territory.

Marland P. Billings, Professor of Geology at Harvard University, has been succeeded as Chairman of the Department of Geology and Chairman of the Division of Geological Sciences by L. Don Leet.

Norris E. Bradbury, Director, Los Alamos Scientfic Laboratory, has been elected to membership in the National Academy of Sciences.

Maurice L. Brashears, Jr., in charge of the office of the Ground-Water Branch of the U. S. Geological Survey in Mineola, New York, has accepted an assignment of several months on water-supply problems in Japan. Norbert J. Lusczynski will be acting in charge of the Mineola office during this interim.

Dirk Brouwer, Director of Yale Observatory, was recently elected a member of the National Academy of Sciences.

Everette L. DeGolyer of DeGolyer and MacNaughton was recently elected to membership in the National Academy of Sciences.

Talcott W. Edminster, Project Supervisor on Research at Blacksburg, Va., for the Soil Conservation Service, was recently given the William A. Jump Memorial Award of the U. S. Department of Agriculture for leadership in soil- and water-conservation activities in Virginia. This is a recently-established annual award to young employees of the Department for high achievement in public administration.

Pentti Eskola, Professor of Geology and Minerology, Helsinki University, Finland, was recently elected a foreign associate of the National Academy of Sciences.

Maurice Ewing, Professor of Geology at Columbia University, presented the 1951 Westbrook Free Lecture of the Wagner Free Institute of Science in Philadelphia. The subject of his address was "Exploration of the Atlantic Basin."

Ruy H. Finch, Director of the Hawaiian Volcano Observatory, retired in February 1951. He had been associated with various aspects of the volcanological work of the U. S. Geological Survey since 1924. He has been succeeded as Director by Gordon A. Macdonald.

George Gamow, Professor of Theoretical Physics at George Washington University, has been designated as a Sigma Xi national lecturer. He will address 14 chapters and clubs on "The Origin and Evolution of the Universe."

Ross Gunn, Director of the Division of Physical Research, U. S. Weather Bureau, has been elected a member of the National Academy of Sciences.

William F. Guyton and Walter N. White, formerly of the Ground-Water Branch of the U. S. Geological Survey, have opened an office as consulting ground-water hydrologists in Austin, Texas, with a branch office in Silver Spring, Md.

Norman Herz of the Department of Geology, Wesleyan University, Middletown, Connecticut, has been given a Fulbright Grant for the study of geology in Greece during 1951-52. He will make a study of the quarries of antiquity, and, in cooperation with archaeologists, will relate his findings to the buildings, sculpture, and artifacts of antiquity.

Kohi Hidaka of Tokyo University has been appointed Walker-Ames Professor of Physical Oceanography of the Oceanographic Laboratories of the University of Washington for the summer of 1951.

Columbus O'D. Iselin, Physical Oceanographer, Woods Hole Oceanographic Institution, was recently elected a member of the National Academy of Sciences.

Chester R. Longwell, Professor of Geology at Yale University, has been elected to the Geological Society of Belgium as a corresponding member.

Robert B. McConnell is now associated with D. Harold Byrd and Associates of Dallas, Texas, as a research geologist.

Thomas B. Nolan, Assistant Director, U. S. Geological Survey, was recently elected to membership in the National Academy of Sciences.

Milner B. Schaefer, formerly chief of the Section of Research and Development of the Pacific Oceanic Fishery Investigations in Honolulu, has been appointed Director of Investigations of the newly formed Inter-American Tropical Tuna Commission in San Diego, California.

Thomas G. Thompson, Director of the Oceanographic Laboratories, University of Washington, was recently elected a member of the National Academy of Sciences.

Chester K. Wentworth, Geologic Engineer for the Honolulu Board of Water Supply for 17 years, has retired at the age of sixty. He now resides at Kilauea Volcano on the island of Hawaii, and is taking up duties as geologist with the U. S. Geological Survey, working at the Hawaiian Volcano Observatory in collaboration with Gordon A. Macdonald, its new Director.

Hurd C. Willett, Professor of Meteorology at Massachusetts Institute of Technology, and Vice President of the Section of Meteorology, AGU, has been given the Award of the American Meteorological Society for his contributions to synoptic meteorology.

Vilhelm Friman Bjerknes, world-renowned Norwegian meteorologist, died in Oslo, Norway, April 9, 1951, at the age of eighty-nine. He was the father of J. A. B. Bjerknes of the University of California.

George W. Carr of the Carr Geophysical Company of Houston, Texas, died December 24, 1950, at the age of fifty-one. He was born in Roanoke, Virginia, and took his baccalaureate degree from Colorado School of Mines in 1925. From 1925 to 1937 he was engaged on geophysical exploration work for the Roxana Petroleum and Shell Oil Company, and from 1937 to 1944 on similar work for the General Geophysical Company. He established his own firm in 1944. He had been a member of AGU since 1947.

Harry L. Collins, Assistant Regional Director of the U. S. Weather Bureau at Fort Worth, Texas, died December 30, 1950, at the age of forty-five. He was born at Van Alstyne, Texas, and studied at North Texas Agricultural College and Southern Methodist University. He had been on the staff of the Weather Bureau since 1929, and a member of AGU since 1942. His professional work included the establishment of a hydrologic network of precipitation stations in parts of Texas.

Owen Bert French, consulting geodesist, retired, died February 1, 1951, in Cleveland, Ohio, at the age of eighty-five. He was born in Cleveland and received his baccalaureate degree from Case School of Applied Science (Case Institute of Technology). He was associated with the U. S. Coast and Geodetic Survey from 1895 to 1915, and then entered on consulting and teaching work. He was Professor of Geodesy and Astronomy at the Institute of Military Surveying of Peking, China, in 1918-19, and of Surveying and Geodesy at George Washington University, Washington, D. C., from 1920 to 1933. He had been a member of AGU since 1930.

Theodore T. Knappen of the Knappen Engineering Company of New York died March 22, 1951, at the age of fifty. He was born in Minneapolis, Minnesota. After a year at the University of California, he entered U. S. Military Academy at West Point from which he graduated in 1920. Until 1923 he was in the military service, then entered civil engineering work in California, and served as hydraulic engineer on the San Francisco Hetch Hetchy water supply development. In 1928 he entered the civil service of the Corps of Army Engineers on Mississippi River flood-control work which he continued until 1934. From 1934 to 1936 he was Chief of the Engineering Division of the Muskingam (Ohio) flood-control project, and during the ensuing year worked with the North Atlantic Division of the Army Engineers. From 1937 to 1942 he was associated with Parson, Klapp, Brinckerhoff, and Douglas on consulting work, and from 1942 until his death was a partner in the firm bearing his name. He became a member of AGU in 1937.

Patrick Marshall of New Zealand died in November 1950 at the age of eighty-two. His outstanding contributions in the field of volcanology, especially in the petrology of the volcanic rocks of the western Pacific, and his location of the tectonic margin of the Pacific basin which he termed the andesite line, established his position firmly among geophysical scientists of the world.

Helen Jeanne Plummer, Geologist and Research Scientist of the Bureau of Economic Geology, University of Texas, died January 11, 1951, at the age of 59. She was born in Muskegon, Michigan, and received her baccalaureate degree from Northwestern University in 1913 and her Master of Science degree from the same university in 1925. The early part of her professional career was with Illinois Geological Survey and Roxana Petroleum Corporation. In 1933, she began her work with the Bureau of Economic Geology. She had been a member of AGU since 1947. Her husband, Frederick B. Plummer, who was also a geologist, died February 17, 1947 [see Trans., v. 29, p. 297, 1948].

THIRTY-SECOND ANNUAL MEETING (1951)

MINUTES, GENERAL ASSEMBLY AND SECTIONS

EVENING SESSION

The Evening Session of the Thirty-Second Annual Meeting was called to order by President Walter H. Bucher at 20h 05m, Monday, April 30, 1951, in the Lecture Room of the National Academy of Sciences, 2101 Constitution Avenue, Washington, D. C. About 200 were in attendance. After preliminary and welcoming remarks, President Bucher introduced John Putnam Marble, who arranged the Symposium on the Measurement of Geologic Time. After introductory remarks, he in turn introduced the authors, Raymond C. Moore and Edward McCrady, who presented their papers as set forth in the Program [see pp. 306 and 313]. He then introduced J. Tuzo Wilson of the University of Toronto, who presented very recent data secured by means of the new mass spectrograph of the University. Discussion followed, including remarks by Robert C. Herman of the Applied Physics Laboratory of Johns Hopkins University.

Following this discussion, Chairman Marble called attention to a continuation of the Symposium on Wednesday afternoon (May 2), and returned the chair to President Bucher, who introduced foreign colleagues in attendance at the meeting. (Those in attendance included 43 from 15 foreign countries as follows: Australia, Bolivia, Canada, Denmark, Eire, England, Finland, France, Iceland, India, Japan, Siam, South Africa, Turkey, and Uruguay.)

President Bucher then introduced Richard H. Fleming, who (on behalf of the Committee on the Award of the William Bowie Medal, and its Chairman, Walter D. Lambert) cited Harald Ulrik Sverdrup as the Thirteenth William Bowie Medalist [see pp. 337-340 of this issue]. President Bucher next made presentation to Erling Christophersen, Cultural Attaché of the Norwegian Embassy, who responded on behalf of Dr. Sverdrup (formal acceptance and response have since come from the recipient) as set forth following the Citation.

The session was then adjourned, and was followed by an informal social hour, with refreshments, in the Auditorium.

SMOKER

A Smoker was held in the Auditorium of the Cosmos Club on Tuesday, May 1, 1951, from 20h 00m to 22h 30m. About 210 were in attendance. This was informal, with no program, but offered opportunity to renew old acquaintances and friendships and to make new ones. Full advantage was taken of these opportunities, and many lively discussions took place.

GENERAL ASSEMBLY: SYMPOSIUM AND BUSINESS MEETING

The General Assembly was called to order by General Secretary Beij at 14h 05m, Wednesday, May 2, 1951, in the Auditorium of the National Academy of Sciences. About 200 were in attendance. The General Secretary turned the chair over to John Putnam Marble, who had arranged the Symposium. The Symposium proceeded as set forth in the Program [see pp. 306, 313, and 314].

Following considerable discussion, Chairman Marble turned the chair over to President Bucher, who called the Business Meeting to order. The minutes of the last meeting [see Trans., v. 31, pp. 485-488] were approved.

Report of the General Secretary--General Secretary Beij summarized the activities of the Union since the Thirty-First Annual Meeting. These are reported in connection with the Minutes of the Meetings of the Executive Committee of November 15, 1950 [see Trans., Feb. 1951, pp. 141-148] and May 2, 1951 [to be published in the August 1951 issue of the Transactions].

A recapitulation of the changes in membership since April 20, 1950, is as follows:

Members, April 20, 1950	4595	
Reactivated	1	
New members (including 61 in process of election)	519	5115
Resignations	223	
Deceased	22	
Active to inactive	17	
Dropped	113	375
Membership as of April 20, 1951		4740

The Annual Report of the General Secretary was accepted.

Reports of Standing Committees

Meetings--Chairman J. P. Marble of the Committee on Meetings announced the dates for the Thirty-Third Annual Meeting as May 5-7, 1952.

Reports of other standing committees were not presented, and will be published in the Transactions.

Reports of Special Committees

Resolutions--Chairman Mary C. Rabbitt presented eight resolutions, which were unanimously adopted as follows:

(1) RESOLUTION OF THANKS FOR USE OF FACILITIES

WHEREAS, The National Academy of Sciences and the United States Public Buildings Administration have made possible the holding of the Thirty-Second Annual Meeting of the American Geophysical Union by providing meeting rooms and other facilities, therefore be it

RESOLVED, That the American Geophysical Union extends its heartiest thanks to the National Academy of Sciences and to the United States Public Buildings Administration for their kindness and cooperation and instructs the General Secretary to forward a copy of this resolution to the appropriate officers.

(2) RESOLUTION OF THANKS TO THE FRESNO STATE COLLEGE

WHEREAS, The success of the Twenty-Sixth Regional Meeting at Fresno, California, February 9-10, 1951, was due in large part to the space and facilities generously provided by the Fresno State College, therefore be it

RESOLVED, That the thanks of the American Geophysical Union be extended to the Fresno State College for the use of their meeting rooms and other facilities, and that the General Secretary be instructed to forward a copy of this resolution to Dr. Arnold E. Joyal, President.

(3) RESOLUTION OF THANKS TO THE CARNEGIE INSTITUTION OF WASHINGTON

WHEREAS, The Carnegie Institution of Washington has for many years provided quarters in its buildings for the officers and staff of the American Geophysical Union, thereby making effective work of the Union possible, and

WHEREAS, The Carnegie Institution of Washington has kindly continued this essential service during the past year, therefore be it

RESOLVED, That the American Geophysical Union most heartily thanks the Carnegie Institution of Washington for its continued interest in the welfare of the American Geophysical Union and requests the General Secretary to forward a copy of this resolution to the appropriate officers of the Carnegie Institution of Washington.

(4) RESOLUTION ON COMMUNICATIONS SERVICES

WHEREAS, The Secretary of Commerce, in cooperation with the Foreign Service Office of the United States, the officers of the Foreign Service, and the Foreign Service Operations Staff of the Office of International Trade, have made available their special telegraphic facilities for transmitting teleseismic data to the United States Coast and Geodetic Survey, and

WHEREAS, The data have greatly accelerated and expanded the earthquake location program of the Survey, and

WHEREAS, The data have been made available by the Survey to seismologists throughout the world to aid in the more thorough analysis of their records, therefore be it

RESOLVED, That the American Geophysical Union express its appreciation for this valuable contribution to seismological research, and be it further

RESOLVED, That copies of this resolution be sent to the Secretary of Commerce, the Foreign Service Office of the United States, the Foreign Service Operations Staff of the Office of International Trade, and officers of the Foreign Service at the following stations: Djakorta, Java; Bombay, India; Brisbane, Australia; Cairo, Egypt; Copenhagen, Denmark; Damascus, Lebanon; Guatemala City, Guatemala; La Plata, Argentina; Lima, Peru; Málaga, Spain; Mexico City, Mexico; Perth, Australia; Rio de Janeiro, Brazil; Rome, Italy; Santiago, Chile; Strasbourg, France; Sydney, Australia; Tananarive, Madagascar; and Pretoria, South Africa.

(5) RESOLUTION ON TIME-SIGNAL SERVICE

WHEREAS, There is a vital need in all seismological work for accurate time service, and

WHEREAS, The time service maintained by the United States Naval Observatory, the Naval Communications Service, and the National Bureau of Standards has been of great use in this work, therefore be it

RESOLVED, That the American Geophysical Union express its appreciation of the valuable scientific cooperation and reiterate its desire for the continuance of this time-signal service, and be it further

RESOLVED, That copies of this resolution be sent to the Secretary of the Navy, the Director of Naval Communications, the Superintendent of the Naval Observatory, the Secretary of Commerce, and the Director of the National Bureau of Standards.

(6) RESOLUTION ON DEATH OF MERRILL BERNARD

WHEREAS, Death has deprived us of the fellowship and services of Merrill Bernard, one of those active in the formation of the Section of Hydrology of the American Geophysical Union in 1932, Chairman of Research Committees throughout several years, contributor to many scientific reports, Vice President of the Section of the Section of Hydrology, and President of the International Association of Scientific Hydrology, therefore be it

RESOLVED, That the American Geophysical Union formally acknowledges the services of the late Merrill Bernard to geophysics, and that a copy of this resolution be sent to Mrs. Bernard and to the Chief of the United States Weather Bureau.

(7) RESOLUTION ON "WORLD DAYS" OR "INTERNATIONAL DAYS"

RESOLVED, That the American Geophysical Union endorses the proposal of the Joint Commission on High-Altitude Research Stations of the International Council of Scientific Unions for the selection of "World Days" or "International Days" with the provision that the plan for the selection of such days be considered in greater detail at the Brussels (1951) Assembly of the International Union of Geodesy and Geophysics.

(8) RESOLUTION ON ESTABLISHMENT OF STANDARD UPPER ATMOSPHERIC NOMENCLATURE LIST

RESOLVED, That the American Geophysical Union endorses the efforts of the Mixed Commission on the Ionosphere of the International Council of Scientific Unions to establish a standard upper atmospheric nomenclature list which is satisfactory to the majority of investigators in the field.

A resolution proposed by the Section of Terrestrial Magnetism and Electricity on the proposed designation of 1957-58 as a Polar Year [see Appendix D] was discussed, modifications suggested, and referred to the Executive Committee. The discussion expressed the thought that the resolution tended to commit AGU too definitely at this time. (In the meeting of the Executive Committee, the modified resolution was discussed, and finally tabled, requiring further action at the fall meeting of the Executive Committee.)

The resolution concerning the Program and Transactions passed by the Section of Meteorology [see Appendix C] was discussed briefly.

The meeting adjourned at 16h 20m.

K. HILDING BEIJ, General Secretary
WALDO E. SMITH, Executive Secretary

APPENDIX A--MINUTES OF THE ANNUAL MEETING OF 1951, SECTION OF GEODESY, AMERICAN GEOPHYSICAL UNION

The Thirty-Second Annual Meeting of the Section of Geodesy was called to order by President Harry H. Hess at 09h 05m, May 2, 1951, in the Auditorium, National Academy of Sciences, Washington, D. C. About 110 members and guests were in attendance.

The minutes of the Thirty-First Annual Meeting were declared approved as published in the Transactions [v. 31, p. 488].

C. A. Whitten, Chairman of the Resolutions Committee, reported no resolutions had been offered.

The Executive Committee reported the appointment of D. A. Rice as United States member of the newly created International Gravity Committee, and continuation of the appointment of F. W. Hough and C. A. Whitten as United States members of the Commission for the Adjustment of the European Triangulation. The Executive Committee asked the Section to approve these actions, which was done.

The presence of several members and guests from foreign countries was recognized.

The scientific papers were presented as shown on the Program for the Section of Geodesy [see p. 307].

The meeting adjourned at 12h 10m.

FRANK L. CULLEY, Secretary

APPENDIX B--MINUTES OF THE ANNUAL MEETING OF 1951, SECTION OF SEISMOLOGY, AMERICAN GEOPHYSICAL UNION

The Thirty-Second Annual Meeting of the Section of Seismology was held April 30 and May 1, 1951, in the Lecture Room, National Academy of Sciences, Washington, D. C. The first session was called to order at 14h 00m, April 30, by President Perry Byerly. The minutes of the 1950 meeting were approved as published in the Transactions [v. 31, pp. 488-489, 1950].

President Byerly appointed a Committee on Resolutions consisting of L. M. Murphy (Chairman), Beno Gutenberg, and Daniel T. O'Connell, to report at the next session. As there was no other business, the Business Session was adjourned and was immediately followed by the first Scientific Session shown on the Program [see p. 307].

The second session was called to order at 09h 00m, May 1, by President Byerly. L. M. Murphy presented two resolutions for action by the Section. These were approved and forwarded to the Union [see Resolutions (4) and (5) in the minutes of the Business Meeting of the Union]. The second Scientific Session was then held as shown in the Program.

JAMES T. WILSON, Secretary

APPENDIX C--MINUTES OF THE ANNUAL MEETING OF 1951, SECTION OF METEOROLOGY, AMERICAN GEOPHYSICAL UNION

The Thirty-Second Annual Meeting of the Section of Meteorology was held May 1, 1951, in the Auditorium of the National Academy of Sciences and of the General Services Building. Approximately 300 members and guests attended the two sessions of the Section.

The opening business session was held from 09h 00m to 09h 30m, May 1, 1951, with President Benjamin Holzman presiding. Since no corrections were received, the President declared the minutes of the Thirty-First Annual Meeting of the Section of Meteorology approved as published in the Transactions [v. 31, p. 489, 1950]. The President then appointed a Committee on Resolutions (Werner A. Baum, Chairman; R. H. Weightman; and Louis P. Allen).

A comprehensive report on "Cloud Seeding," prepared by the Committee on Cloud Physics, was read by the Chairman, Horace Byers. A brief report was given by the Meteorological Editor, Philip F. Clapp. The reports of the Committees on Atmospheric Diffusion, Problems of the Upper Atmosphere, and Climatology were read by title.

As there was no other business, the Business Meeting was adjourned and immediately followed by the schedule of scientific papers shown on the Program [see p. 308].

At the termination of the last scientific paper, Presiding Chairman Horace Byers called for a report of the Committee on Resolutions. One resolution, pertaining to the compartmentalizing of articles in the Transactions and to the initiation of an "All-Union Session" in the schedule of the spring meetings, was presented as follows:

RESOLVED, That the Union hold at least one session at the annual meeting devoted to general geophysics, to include papers of interest to two or more Sections, and that, where appropriate, papers in the Transactions be classified as "General" rather than by section.

The resolution was unanimously approved by the Section and forwarded to the Union for action.

The meeting adjourned at 17h 00m.

WOODROW C. JACOBS, Secretary

APPENDIX D--MINUTES OF THE ANNUAL MEETING OF 1951, SECTION OF TERRESTRIAL MAGNETISM AND ELECTRICITY, AMERICAN GEOPHYSICAL UNION

The Thirty-Second Annual Meeting of the Section of Terrestrial Magnetism and Electricity of the American Geophysical Union was held on April 30 and May 1, 1951. The first session was called to order at 14h 03m on Monday, April 30, in the Auditorium of the General Services Building by President J. Wallace Joyce. There were about 120 members and guests in attendance. The minutes of the previous meeting were approved as published in the Transactions [v. 31, pp. 490-491, June 1950].

By a vote of the members present, E. O. Hulburt was designated at the Chief Delegate by this Section to the meeting of the Association of Terrestrial Magnetism and Electricity to be held in conjunction with the Ninth General Assembly of the International Union of Geodesy and Geophysics to be held in Brussels, Belgium, in August 1951. Joseph Kaplan was elected to act as an alternate.

President Joyce appointed E. O. Hulburt, E. B. Roberts, E. H. Vestine, and A. H. Shapley as a working group to consider resolutions for presentation to members at the second session.

After the routine announcements, the scientific program was begun in accordance with the Program [see pp. 308-309 and 320-323]. The first session adjourned at 16h 55m.

The second session was convened at 14h 05m on Tuesday, May 1.

President Joyce presented three resolutions which were submitted by the working group. Two appear in the minutes of the Business Meeting of the Union as Resolutions (7) and (8). The third one, relating to a Third Polar Year, on which action by the Union was deferred, as reported in the minutes of the Business Meeting, is as follows:

RESOLUTION--The American Geophysical Union heartily endorses the proposal of the Mixed Commission on the Ionosphere of the International Council of Scientific Unions for the establishment of a Third Polar Year in 1957-58 and the American Geophysical Union subscribes to the recommendations accompanying this proposal, namely, that: (a) The year 1957-58 be designated as International Polar Year. (b) A Commission be set up by ICSU similar to that established for previous polar years to encourage, through the various Unions and their National Committees, the establishment of a proper network of observing stations. (c) In view of the complexities of the apparatus needed to exploit the potentialities of modern technique, the above Commission be established in 1951, so as to give at least five full years of preparation and trial. (d) A permanent secretariat should be formed to operate during the most active period of the Commission's work, from about two years prior to the polar year until about three years after the polar year.

All three resolutions were approved and sent to Mary C. Rabbitt, Chairman of the AGU Committee on Resolutions, for action by the Union.

After routine announcements, the remaining technical papers were presented as printed in the Program except paper (19), which was read by title. The meeting was adjourned at 16h 35m.

L. R. ALLDREDGE, Secretary

APPENDIX E--MINUTES OF THE ANNUAL MEETING OF 1951, SECTION OF OCEANOGRAPHY, AMERICAN GEOPHYSICAL UNION

The Thirty-Second Annual Meeting of the Section of Oceanography was held in Washington, D. C., on April 30, 1951. The first session convened at 09h 00m in the Auditorium of the General Services Building and adjourned at 12h 30m. The second session met at 14h 00m in the Auditorium

of the National Academy of Sciences and adjourned at 16h 30m. President A. C. Redfield presided at both sessions.

As no corrections were offered to the minutes of the previous annual meeting, published in the Transactions [v. 31, p. 491, June 1950], they were approved.

The Secretary pointed out that titles of papers to be presented at the meetings of the International Union of Geodesy and Geophysics, to be held in Brussels in August 1951, should be forwarded to him as soon as possible. Also, it was stressed that the names of those planning to attend these meetings should be made known to the American Geophysical Union immediately.

The scientific program of the two sessions consisted of presentation and discussion of the papers listed in the Program [see p. 309] as amended.

Changes to the Program were as follows: Paper (1) was read by Dale F. Leipper. Paper (2) was read by title. Papers (7) and (9) were read by the Secretary. Paper (15) was read by title, and paper (16) was read by R. A. Gordon. Phil E. Church informed those at the second session of the recent reorganization of the Oceanographic Laboratories of the University of Washington. This activity has been made a department of the University and, beginning in the fall of 1951, will offer undergraduate courses as well as graduate work in oceanography.

At the conclusion of the regular meeting Pierre Danel of Grenoble, France, presented a motion picture showing model studies of the effects of waves upon breakwaters of different designs.

RICHARD H. FLEMING, Secretary

APPENDIX F--MINUTES OF THE ANNUAL MEETING OF 1951, SECTION OF VOLCANOLOGY, AMERICAN GEOPHYSICAL UNION

The Business Meeting of the Section of Volcanology was called to order by President Larsen at 09h 15m, April 31, 1951. The President reminded the members of the impending IUGG meeting in Brussels. It was moved by E. F. Osborn and passed by voice vote that the Executive Committee of the Section be empowered to make necessary decisions regarding representation at the Brussels meeting.

In response to the request made at the last meeting of the Executive Committee of the Union, Vice-President Thayer then presented a series of motions and supporting arguments prepared by the Executive Committee of the Section, designed to sound out the sentiments of the Section with regard to the parallel questions of setting up a separate Section of Geochemistry and of renaming the Section of Volcanology. To save time it had been intended that each of these motions be discussed and voted upon as read. On objection by L. C. Graton, shared by many in attendance, the entire set of motions and supporting arguments were read before the voting. The motions were then re-read and voted upon separately, after considerable discussion and amendment of the first two. All were approved unanimously. The motions as amended are as follows:

(1) In view of its own present interest in geochemistry and petrology, and as it would set up in competition two sections whose interests are largely shared, the Section of Volcanology is opposed to the creation of a separate Section of Geochemistry at the present time.

During the discussion of this motion M. Fleischer, a member of the International Chemical Union's (ICU) new "Commission on Localization of the Elements," described plans of that organization. These plans are mostly concerned with bibliographical and administrative problems at the organization level. As the ICU has only organizational members, any action involving individual geochemists in this country will have to be made through one of its American affiliates. The American Chemical Society has a Section of Geochemistry which, though dormant for many years, is again showing signs of life. Fleischer desired to stress that he was appearing at the request of the Executive Committee of our Section and did not desire that his remarks be construed as opposed to any action the Section or Union might care to take. Some duplication in organizations dealing with borderline sciences was inevitable, and often helpful to all concerned.

(2) The Section of Volcanology feels that changing its title to "Volcanology and Igneous Petrology" would clarify its role in the Union and strengthen its appear to qualified persons not now affiliated with the Union.

The original motion proposed "Petrology and Geochemistry" as the new title. Earl Ingerson,

Chairman of the Union's Committee to Consider the Formation of a Section of Geochemistry and Radioactivity [Trans., v. 32, p. 148], stated that he had had considerable correspondence over the matter, that there was general opposition to the creation of a separate Section of Geochemistry at this time and general approval of a change in the name of the Section of Volcanology, but little agreement about any particular new name. Since his Committee had been organized, the problem of an outlet for geochemical papers had been solved by the appearance of Acta Geochimica, and there was even talk now of forming a separate American Geochemical Union. Before seeing the slide which illustrated Thayer's discussion he had not realized how small a part papers in geochemistry played in the Section's programs. Although nearly everyone he approached had agreed that a change of name was in order, many wanted to retain "Volcanology" in the new title. He himself had no strong preference, but his Committee report proposed "Volcanology and Geochemistry."

Howel Williams was among those anxious to retain "Volcanology" in the new title, and his argument to this effect was well received. He proposed "Volcanology and Igneous Petrology" as a replacement for "Petrology and Geochemistry" in the Section Committee's motion. The amendment was accepted and the amended motion was passed unanimously. After the vote E. F. Osborn pointed out that many petrologists regard the word "igneous" as meaningless or misleading. The audience showed no disposition to reopen the discussion in response to this suggestion.

The remaining motions concern only the timing of whatever action is to be taken, and were passed unanimously after cursory discussion. They are:

(3) The Section of Volcanology is opposed to initiation of final action with regard to renaming it or creating a new Section of Geochemistry until the fall meeting of the Union's Executive Committee.

(4) The Section of Volcanology respectfully requests that the questions of creating a separate Section of Geochemistry and of renaming the Section of Volcanology be discussed together and voted upon at the fall meeting of the Union's Executive Committee.

(5) The Section of Volcanology respectfully requests that the American delegate to the Brussels conference be instructed to present resolutions (1) and (2) for discussion as representing the views of the American committee of the International Association of Vulcanology pertaining to reorganization of the IUGG.

At the conclusion of the voting, C. S. Ross read an obituary of P. Marshall of New Zealand, and expressed the regret of the Section at the death of this elderly and distinguished student of volcanic rocks.

The Business Meeting was adjourned at 09h 50m. The well-attended technical session which followed was completed at 13h 00m. Many members felt that there would have been more extended discussion of several of the papers if more time had been available. The program was as previously announced.

FELIX CHAYES, Secretary

APPENDIX G--MINUTES OF THE ANNUAL MEETING OF 1951, SECTION OF HYDROLOGY, AMERICAN GEOPHYSICAL UNION

The Annual Meeting of the Section of Hydrology of the American Geophysical Union was held April 30 and May 1, 1951, in the Auditorium of the National Academy of Sciences and the Auditorium of the General Services Building in Washington, D. C. Walter B. Langbein, acting for President F. J. Veihmeyer, called the first session to order at 09h 00m, April 30, in the Auditorium of the National Academy of Sciences.

The untimely death of Vice President Merrill Bernard was cited. The vacancy created by his death will be filled in accordance with Statutes of the Section and of the Union. Information regarding this matter will be announced in a subsequent issue of the Transactions.

Presiding Chairman Langbein announced that the South Pacific Region had been formally inaugurated by the appointment of H. F. Blaney, Harold Conkling, and J. W. Johnson to represent the Section of Hydrology and E. M. Vernon, R. H. Simpson, and Morris Neiburger to represent the Section of Meteorology. These will act as a Committee of the Union for the South Pacific Region, with J. W. Johnson as Chairman. No other sections are participating at present.

In view of the interest indicated in the North Pacific area, steps are being taken to appoint a

Regional Committee for the Section of Hydrology. Other Sections have not yet expressed their interest. The Executive Committee will continue to survey the interest in other regions and will welcome expressions from members concerning their desires for regional organizations.

Announcement was made that the triennial meeting of the International Association of Hydrology will be held in Brussels, Belgium, from August 21 to September 1, 1951. A. N. Sayre is Chairman of the Commission on Subterranean Waters, and W. C. Lowdermilk is Chairman of the Commission on Land Erosion. Contributions from the United States are being coordinated as follows: Surface Waters, J. V. B. Wells; Subterranean Waters, A. N. Sayre; Snow and Ice, W. O. Field, Jr.; Land Erosion, Carl B. Brown. Further information concerning the meeting will appear in later Transactions.

The South Pacific Region held a successful meeting at Fresno State College, Fresno, California, on February 9-10, 1951, with the Sections of Meteorology and Hydrology participating.

Carl F. Izzard, Acting Chairman of the Committee on Honors and Awards, announced that the Committee had not yet completed the review of Section papers published in the Transactions of 1950. The recommendations of the Committee will be submitted to the Executive Committee as soon as practicable.

A resolution, in recognition of the services of Merrill Bernard, was adopted by the Section and forwarded to the Union for ratification [see Resolution (6) in the minutes of the Business Meeting of the Union].

There being no further business, the technical session proceeded according to the Program [see pp. 310-311 and 329-333], except for the following: Report (R1) by Hastings was presented by title.

The first session recessed at 12h 30m.

Herbert S. Riesbol acted as Presiding Chairman for the second session at 09h 10m, May 1, 1951, in the Auditorium of the General Services Building. The Program was followed with the exception of the following: Paper (11) by Work, Nelson, and Wilm was presented by Bernard Frank. Report (R7) by Peterson was presented by L. B. Leopold. Paper (14) by Albertson was presented by Thomas Maddock. Report (R8) by Bodman was presented by title.

The session adjourned at 11h 45m.

Walter U. Gartska acted as Presiding Chairman and called the final session together at 14h 00m, May 1, 1951, in the Auditorium of the National Academy of Sciences. The published Program was followed with the following exceptions: Reports (R10), (R11), and (R12), and paper (16) were presented by title.

Before beginning the Symposium on Phreatophytes, the Chairman called upon W. A. Liddell, 1950 Chairman of the Subcommittee on Hydrology, Federal Inter-Agency River Basin Committee, who gave a report on the organization and current activities of the Subcommittee.

Paper (18) by Blaney was presented by C. B. Brown, and paper (20) by Turner and Skibitzke was presented by T. W. Robinson.

Ralph N. Wilson read excerpts of a letter from Secretary R. K. Linsley, quoting remarks by L. J. Tison, Secretary, International Association of Hydrology, concerning the untimely death of Merrill Bernard.

The meeting adjourned at 16h 25m.

R. N. WILSON, Acting Secretary

APPENDIX H--MINUTES OF THE ANNUAL MEETING OF 1951, SECTION OF TECTONOPHYSICS, AMERICAN GEOPHYSICAL UNION

The Annual Meeting of the Section of Tectonophysics was held on Wednesday morning, May 2, 1951, in the Lecture Room of the National Academy of Sciences, Washington, D. C. The meeting was called to order by President Robert Balk at 09h 00m. The minutes of the previous meeting were approved as published in the Transactions [v. 31, p. 493]. The President announced that the Section had no committee reports to present and inquired if there was any new business for con-

sideration. None was presented, and the Business Meeting was closed.

The scientific program of the Section, consisting of eight papers as set forth in the Program (see p. 311), started at 09h 05m and was adjourned at 12h 30m.

W. S. BURBANK, Secretary

TWENTY-SIXTH MEETING

The Twenty-Sixth Meeting was held in the South Pacific Region at Fresno State College, Fresno, California, February 9-10, 1951. The Sections of Hydrology and Meteorology arranged and held this jointly. It was the first time the South Pacific Meeting was held on the Fresno College campus, which is the approximate geographic center of the State.

Over 200 persons attended the combined sessions on Friday morning, February 9, and of this number 130 were registered members or guests. The papers presented covered a wide range of subjects directly related to or closely allied to the fields of Hydrology and Meteorology. In all, 26 papers were read.

The dinner meeting on Friday evening, February 9, had 112 in attendance. A. D. Edmonston, Engineer, State of California Department of Public Works, delivered the evening address on "Water resources of California."

The sessions closed with a field trip to the construction area of Pine Flat Dam. The participants on this field trip were especially impressed with the engineering problems related to geological structure of the formations in which the base of the dam is located. This was well illustrated by the use of and explanation of plastic models showing the structural conditions.

Fresno State College was distinctly honored by being selected as the host for this Southwest Pacific Meeting of the Union. The Union's Committee arranging the meeting consisted of A. R. Addington, General Chairman, with A. A. Lothman, V. C. McKim, and C. B. Nelson arranging matters for Meteorology, and Harry F. Blaney, Martin R. Huberty, W. J. Parsons, and J. F. Poland for Hydrology. Tentative plans were laid for working out a formalized regional committee.

A. R. ADDINGTON, Chairman

SPECIAL ANNOUNCEMENTS

Dates set for Thirty-Third Annual Meeting--The Thirty-Third Annual Meeting of the American Geophysical Union will be held in Washington, D. C., May 5-7 (Monday-Wednesday), 1952. Mark these dates on your calendar now and make plans to attend. This will serve as a first call, also, for titles and abstracts of papers for the meeting. Please communicate any suggestions you may have for symposia, panel discussions, or other features for the program, to the Chairman of the Committee on Meetings, to the appropriate Section Secretary, or to the office of AGU.

Meeting in Chicago in September 1952--Tentative plans are being made for a meeting in Chicago in September 1952 in connection with the Centennial of Engineering celebrating the 100th anniversary of the founding of the American Society of Civil Engineers. Under present plans, the Sections of Meteorology and Hydrology, at least, will join in this meeting, and it will be broadened to include other Sections, as indicated by the desires of members who reside in the Middle West, or who reside elsewhere, but desire to take part in such a meeting. Write to Mr. Glenn E. Stout (member of the Committee on Meetings in that area), 708 N. Lincoln St., Urbana, Illinois, the officers of the appropriate Sections, or the office of AGU, expressing your thoughts on this matter.

GEOPHYSICAL RESEARCH CORPORATION

Geophysical Prospecting
Application of Geophysical Methods in the Petroleum Industry

2607 North Boston Place
Tulsa 6, Oklahoma

GULF RESEARCH & DEVELOPMENT COMPANY
GULF OIL CORPORATION

Geophysical and Other Research
Relating to the Petroleum Industry

P. O. Drawer 2038
Pittsburgh 30, Pennsylvania

INSTITUTE OF GEOPHYSICS

UNIVERSITY OF CALIFORNIA

Los Angeles 24, California

RANNEY METHOD WATER SUPPLIES, INC.

Ground Water Exploration and Development

841 Alton Avenue
Columbus 3, Ohio

RUSKA INSTRUMENT CORPORATION

Developers, Designers, and Manufacturers of Instruments for Field and Observatory Use
Magnetic, Geodetic, Seismic, and Meteorological Work

4607 Montrose Boulevard
Houston 6, Texas

SEISMOGRAPH SERVICE CORPORATION

Seismic Exploration Service for
Oil and Gas Structures throughout the World

P. O. Box 1590
Kennedy Building
Tulsa 1, Oklahoma

SPRENGNETHER INSTRUMENT COMPANY

Manufacturer of Seismological and Geophysical Instruments
Instrumental Development and Research

4567 Swan Avenue
St. Louis 10, Missouri

TRANSACTIONS
AMERICAN GEOPHYSICAL UNION

Volume 32 AUGUST, 1951 Number 4

COLLOQUIUM
ON PLASTIC FLOW AND DEFORMATION
WITHIN THE EARTH

Hershey, Pennsylvania
September 12-14, 1950

Under the joint sponsorship of
International Union of Geodesy and Geophysics
and
International Union of Theoretical and Applied Mechanics
Aided by a subvention from
United Nations Educational, Scientific, and Cultural Organization

Special Editorial Committee

B. Gutenberg (Chairman) — Seismological Laboratory, California Institute of Technology, Pasadena, Calif.

Hugo Benioff — Seismological Laboratory, California Institute of Technology, Pasadena, Calif.

J. M. Burgers — Institute of Technology, Delft, Holland

David Griggs — University of California, Los Angeles, Calif.

COLLOQUIUM

CONTENTS

Introduction . . . . . L. H. Adams 499

Part I - Inelastic Deformation of Material
Basic Concepts Concerning Deformation of Materials Under Stress . . . J. M. Burgers 500
Discussion . . . . . Jean Goguel 504
Some Mechanical Questions about the Deformation of Rocks . . . . . A. Nadai 504
Some Experiments Bearing on the Plasticity of Rocks in the Earth . . . David Griggs 505
Discussion 507
Crustal Strain Characteristics Derived from Earthquake Sequences . . . . Hugo Benioff 508

Part II - Formation of Folded Belts and Geosynclines
Fundamental Properties of Orogenic Belts . . . . . W. H. Bucher 514
On the Origin of Geosynclines, Mountain Formation, and Volcanism . . P. P. Bijlaard 518
Discussion 519
Remarks on Deformation of the Earth's Crust . . . . . E. C. Bullard 520
Discussion . . . . . Jean Goguel, J. M. Burgers 520
Thermodynamic Theory of Peri-Continental Liminary Zones . . . . . M. L. Glangeaud 521
Deformation of the Earth's Crust in Geosynclines . . . . . F. A. Vening Meinesz 523

Part III - Gravity Anomalies and Postglacial Uplift
On the Postglacial Uplift of Land in Fennoscandia . . . . . W. Heiskanen 524
Discussion . . . . . David Griggs, E. C. Bullard, Beno Gutenberg 525
On the Large Positive and Negative Gravity Anomaly Fields . . . . . W. Heiskanen 525
Discussion . . . . . P. P. Bijlaard, David Griggs, Jean Goguel 526

Part IV - Convection Currents
Summary of Convection-Current Hypotheses of Mountain Building . . . . . David Griggs 527
Comment on Mountain Building . . . . . H. H. Hess 528
Discussion 531
Convection Currents in the Mantle . . . . . F. A. Vening Meinesz 531
Remarks on the Structure of the Mantle, and its Bearing upon the Possibility of Convection Currents . . . . . Francis Birch 533
Discussion 534
The Hypothesis of Convection Currents in the Earth . . . . . J. H. F. Umbgrove 535
Discussion . . . . . P. P. Bijlaard 535
On Some Possibilities Offered by the Study at Planetary Scale of Terrestrial Phenomena . . . . . J. F. Cox 536
Discussion 537
Fluid Motion of Earth's Interior as Inferred from Geomagnetism . . . . E. H. Vestine 537
Discussion . . . . . E. C. Bullard 538

Summary - Colloquium on Plastic Flow and Deformation Within the Earth . . B. Gutenberg 539

References (for entire Colloquium) 542

INTRODUCTION

L. H. Adams

Many problems in geophysics involve motions in the material of the Earth far below the surface. For example, the wandering of the Earth's magnetic pole suggests that there is a slow movement of something deep within the Earth. Similarly the shift in the Earth's axis of rotation has been thought to be connected with some sort of motion or plastic deformation in the interior. Moreover, the formation during geologic history of great areas of depression – geosynclines – has been thought by many geophysicists to find its simplest explanation on the assumption of convection currents that extend to great depths. These phenomena are of interest alike to two International Unions, that of Geodesy and Geophysics and that of Theoretical and Applied Mechanics; and it was only natural that officers of these two Unions should consider means of bringing together a representative group for an extended discussion of plastic flow and deformation within the Earth. President F. A. Vening Meinesz of the International Union of Geodesy and Geophysics, together with Secretary J. M. Burgers of the International Union of Theoretical and Applied Mechanics, took the initial steps in making the arrangements for a Colloquium that would provide an opportunity for full, free, and informal discussion of the subject. With approval of the other officers of the two Unions, Vening Meinesz appointed an Organizing Commission for setting up such a Colloquium. The members consisted of

W. Prager, Brown University, Providence, Rhode Island
F. A. Vening Meinesz, Royal Netherlands Meteorological Institute, De Bilt, Holland
B. Gutenberg, Seismological Laboratory, California Institute of Technology, Pasadena, California
H. L. Dryden, National Advisory Committee for Aeronautics, Washington, D. C.
J. M. Burgers, Institute of Technology, Delft, Holland
L. H. Adams, Geophysical Laboratory, Carnegie Institution of Washington, Washington, D. C.

The last named was invited by Vening Meinesz to act as Secretary; and, with the approval of the officers of the two Unions, the Secretary designated as a Local Committee on Arrangements those members of the Organizing Commission resident in Washington, and, in addition, J. A. Fleming and M. A. Tuve, with E. G. Fullinwider as Executive.

It was understood by all concerned that the meeting should be of the nature of a colloquium rather than of the more conventional type of meeting; that the group should be kept small; and that the participants should represent equitably both the Unions, and should be apportioned about equally between scientists from the United States and from other countries. For the sake of all-around convenience, the time of the meeting was chosen to be the three days beginning September 12, 1950; and, in accordance with the understanding that the meeting should be held in the general vicinity of Washington, the Hershey Hotel at Hershey, Pennsylvania, was selected as the meeting place. The participants in the Colloquium were as follows:

L. H. Adams, Secretary	Geophysical Laboratory, Carnegie Institution of Washington
Hugo Benioff	Seismological Laboratory, California Institute of Technology
P. P. Bijlaard	Cornell University
Francis Birch	Dunbar Laboratory, Harvard University
Walter H. Bucher	Columbia University
E. C. Bullard	National Physical Laboratory of Great Britain
J. M. Burgers	Institute of Technology, Delft
J. F. Cox	Free University of Brussels
H. L Dryden	National Advisory Committee for Aeronautics
B. G. Escher	Leiden University
E. G. Fullinwider, Executive	Geophysical Laboratory, Carnegie Institution of Washington
M. L. Glangeaud	Faculty of Sciences of Besancon
Jean Goguel	Ecole des Mines, Paris

David Griggs	University of California at Los Angeles
B. Gutenberg	Seismological Laboratory, California Institute of Technology
W. Heiskanen	Ohio State University
H. H. Hess	Princeton University
A. Nadai	Research Laboratories, Westinghouse Electric Corporation
Folke K. G. Odquist	Swedish Royal Institute of Technology
W. Prager	Brown University
W. W. Rubey	U. S. Geological Survey
E. H. Vestine	Department of Terrestrial Magnetism, Carnegie Institution of Washington
J. H. F. Umbgrove	Institute of Mines, Delft
F. A. Vening Meinesz	Royal Netherlands Meteorological Institute

Travel expenses were defrayed by means of a grant from UNESCO. Other expenses were defrayed by a substantial donation by E. L. DeGolyer of Dallas, Texas, and by financial support by the Department of Terrestrial Magnetism and the Geophysical Laboratory, Carnegie Institution of Washington.

Most of the group assembled in Washington and proceeded by automobile to Hershey, Pennsylvania. In the quiet and attractive surroundings of the resort hotel the members of the Colloquium carried on discussions both in scheduled meetings and in informal conversations. The Colloquium differed from the usual type of symposium in not having a fixed program. A Moderator was designated for each meeting to guide the discussion, and by common agreement a range of topics was scheduled at the beginning of the session. Beyond this there were practically no formalities.

Just at the close of the meeting a few of the participants met together to talk over the possibility of having a brief report on the subject matters discussed at the Colloquium. Although the primary objective was to provide an opportunity for leisurely and informal discussion of plastic flow and deformation within the Earth, and although the preparation of a report was not considered to be a requirement of the Colloquium, nevertheless it seemed to the group that further important benefits would be derived if at least a summary of the main topics covered were to be assembled and published. The group discussing this pertinent matter was in unanimous agreement that an attempt should be made to have a report that, in addition to an introductory statement and a summary, would include a series of short articles in which the persons in attendance would present briefly the matters touched upon by them in the course of the meeting.

To this end an Editorial Committee consisting of Benioff, Burgers, and Griggs, with Gutenberg as Chairman, was set up and the participants in the Colloquium were notified that brief written statements from them summarizing the remarks at the meeting would be welcome. A number of manuscripts were duly received, correlated, and edited by the Committee. The present report, in addition to an Introduction and Summary, consists of four parts: Inelastic Deformation of Material; Formation of Folded Belts and Geosynclines; Gravity Anomalies and Postglacial Uplift; and Convection Currents.

Of necessity there is here no extended treatment of many of the numerous important subjects covered, but the report will serve to indicate the topics that seemed of special interest to those attending the Colloquium and to call attention to some outstanding problems in the borderland between mechanics and geophysics.

Geophysical Laboratory,
Carnegie Institution of Washington,
Washington, D. C.

PART I - INELASTIC DEFORMATION OF MATERIAL

BASIC CONCEPTS CONCERNING DEFORMATION OF MATERIALS UNDER STRESS

J. M. Burgers

As a preliminary to the analysis of experimental data on the behavior of rocks under pressure and under shearing stresses, it may be helpful to give a short summary of some basic notions which have to be kept in mind in discussions on this subject. In doing so we shall consider the case

of shear, since this gives the simplest geometrical pattern. Complications arising from the simultaneous presence of deformation in different directions will be left aside. Want of space imposes still further restrictions and for a more complete treatment the reader may be referred to BURGERS and SCOTT BLAIR [1949, see References at end of Colloquium].

Many data concerning the behavior of a material under the action of forces producing deformations are given by means of stress-strain curves. In the majority of cases, however, the relation between deformation and stress involves time, and this in such a way that not only the duration of the experiment but the whole history may have influence. Moreover, in many substances, every deformation produces irreversible changes of internal structure, and the repetition of an experiment with the same specimen appears to be impossible. It will be evident, therefore, that, in general, a single stress-strain curve gives only a partial view of the behavior; it cannot picture more than a special case, characteristic for the type of experiment carried out, but does not provide full data for predicting the behavior of the material in other experiments.

Although we seldom can do away completely with limitations of this kind, it is possible and desirable to carry out the experiments in such a manner that at least some insight is obtained both in structural changes and in the influence of time. For this purpose it is necessary to distinguish between permanent deformations of the material, remaining after the load has been taken away, and recoverable deformations, which disappear on removal of the load.

As mentioned, the geometrically most simple case is obtained when we consider the shear produced in a slab of the material by the application of a shearing force. A number of the following considerations can be applied also to the extension of a rod, or to the compression of a block, but the change of cross dimension appearing in such cases introduces certain complications.

We assume that we have at our disposal an unlimited number of identical samples of the material. A sample is now subjected to a constant shear stress τ, during a period t, after which the stress is taken away. Constant temperature is understood, also after the removal of the stress. Likewise other external circumstances should be kept the same, for example, humidity; or, in other cases, small shocks to which the specimen may be subjected during the experiment. (As an exception, it is mentioned that in the investigation of so-called stimulated recovery certain circumstances are purposely changed after unloading (see below).) We observe the course of the shear γ as a function of the time, both during the period and after this period; this may give a curve, for example, of the form sketched in Figure 1. From this curve we deduce (a) the total shear γ_t obtained at the end of the period t; (b) the permanent shear γ_p, finally remaining when the stress has been taken away, after we have waited long enough; and (c) the recoverable part of the shear, defined by the difference $\gamma_e = \gamma_t - \gamma_p$, which often is called the elastic part of the shear. It is possible that either γ_e or γ_p is zero.

The experiment is next repeated (every time on a fresh sample of material), with the same value of the stress τ, but with different values of the duration t. It can be expected that γ_e will become independent of t, provided t is not too small. We can then study the relation between this final value of γ_e and the stress τ, in order to obtain information concerning the elastic properties of the material. For instance, it may appear that within a certain domain the final value of γ_e is simply proportional to τ (Hookean elasticity).

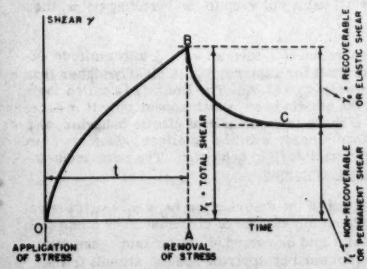


Fig. 1--Standard experiment

For our present purpose, however, more important is the behavior of the permanent shear as a function of t (for a constant value of the stress τ), which behavior we can picture by means of a so-called flow curve. By constructing flow curves for various values of the shear stress τ, we obtain a flow diagram (see Fig. 2).

If it appears that γ_p increases with t (for a given τ), we say that the material flows. There can be limited flow when γ_p has an asymptotic limit for given τ; or unlimited, when, for a given τ, γ_p increases continually with increasing t. Unlimited flow can be decelerated, uniform, or accelerated.

A flow curve may end at a certain value of t through failure of the material (rupture). With

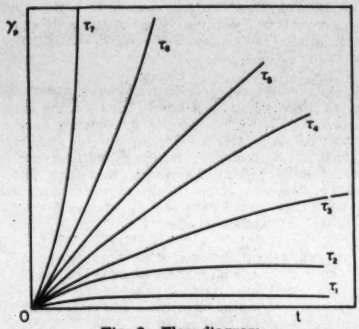


Fig. 2--Flow diagram

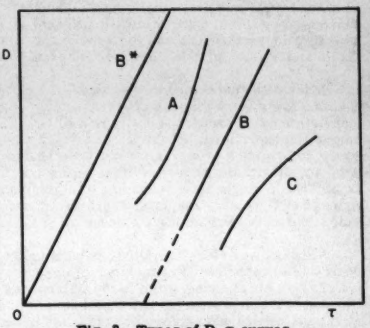


Fig. 3--Types of D-τ curves

certain values of the stress τ, no rupture may occur, independent of the duration t of the experiment. With other (larger) values it may occur when this duration has reached a certain length.

If there appears to be uniform flow (the flow curve being a straight line, or approaching to a straight line when t is large enough), we can determine the derivative $d\gamma_p/dt = D$ (rate of shear). It is then possible to represent the rate of shear as a function of τ, giving a shear rate - stress curve or viscosity curve (see Fig. 3). The extent of this curve will often be limited, both at the side of the smaller τ, if no uniform flow is obtained with τ below a certain limit, and at the side of the larger τ, if too large a τ produces accelerated flow or rupture. (With certain substances a large value of τ sometimes can lead to a limited deformation, even when smaller values of τ call forward unlimited flow.)

The magnitude of the viscosity is defined by the quotient τ/D for any point on a viscosity curve. The value so obtained will in general be a function of the shear rate. When τ/D is independent of the shear rate, the flow is said to be Newtonian.

The series of experiments further need to be carried out according to the same scheme, but at different temperatures and perhaps also with different surrounding pressures, if it is desired to obtain data on the properties of the material under a variety of circumstances. In the following lines we keep to a single temperature and a single pressure.

We return to the flow diagram (Fig. 2), giving γ_p as function of τ (applied stress) and t (duration of loading). With certain materials γ_p appears to be zero for all τ below a certain limit τ_f; or it may be that for such τ the value of γ_p remains very small in comparison with that of γ_e, even when t is taken large. The material then behaves either perfectly or nearly elastically for these values of τ. If elastic behavior is found for all values of τ up to the breaking point, the material is said to be brittle.

If there is elastic behavior for $\tau < \tau_f$, while permanent deformations γ_p, in magnitude exceeding γ_e, appear when $\tau > \tau_f$ (assuming that the limit for rupture, τ_r, is clearly higher than τ_f), the material is said to behave plastically for τ between τ_f and τ_r. The limit τ_f is called the yield stress. Permanent deformations exceeding the elastic ones, which appear only if τ exceeds the yield value, are called plastic deformations. If there is no domain of elastic behavior, and permanent deformations with $\gamma_p > \gamma_e$ can be obtained already with the smallest values of τ (provided t is taken long enough), the material is said to exhibit fluid behavior. The permanent deformations appearing in this case are called fluid deformations.

When attention is returned to the recoverable part of the deformation ($\gamma_e = \gamma_t - \gamma_p$), the recovery is said to be spontaneous when it occurs without any change of circumstances other than the removal of the load. The recovery can be either rapid or retarded. In certain cases stimulated recovery (also called redress) can be called forward by applying special stimuli to the specimen (for instance, small shocks, called mechanical redress; or increase of temperature, called thermo redress).

When the recovery is very slow, the term creep recovery is proposed. In many papers the term elastic after-effect has been used. The counterpart of this phenomenon is a very slow establishment of the recoverable part of the deformation, which is called creep.

We have considered thus far experiments performed every time on a fresh sample. Experiments repeated with the same specimen can next reveal whether there are phenomena of hardening or of softening (for instance, whether there appears an increase or a decrease of a yield value). These experiments can be performed in such a way that time effects can be analyzed, and also the effect of particular changes of circumstances, as, for example, a temporary change of temperature in between successive experiments. We must leave the subject, however, at this point.

Addendum--With reference to terms used in some of the other papers presented at the Colloquium, the following observations may be useful.

(1) The term creep is used by various authors in a different way. Often it is not stated what is the precise meaning assigned to it. In many cases it is used simply as denoting a slowly increasing deformation, without distinguishing between increase of the recoverable part of the deformation and increase of the permanent part. NADAI [1937] applies the term creep to the slow increase of the permanent deformation, so that for him the term creep (also in his paper below) has the same meaning as our slow flow. On the other hand, there are many authors who explicitly reserve the term creep to the slow increase of a recoverable deformation only (with the term creep recovery to denote the inverse phenomenon or elastic after-effect), as it was indicated in our text.

(2) Also the term hardening is sometimes used in a slightly different way from that proposed in our text. NADAI [1937] applies it in the case where (a) the application of a given stress produces a limited permanent deformation and (b) the magnitude of this deformation, considered as a function of the applied stress, appears to increase more slowly than would correspond to the case of proportionality. No attention is given to the recoverable part of the deformation. In the definition given in our text, in accordance with the practice observed by other authors, the term hardening refers explicitly to the increase of the yield value in consequence of the deformation. To be precise it should be tested whether this has occurred by unloading the specimen and subjecting it to a renewed test, although in many cases there will be no doubt about this point.

(3) In our text all considerations had been restricted to the case of simple shear. The question naturally presents itself how these considerations can be extended to other types of deformation. No general rule can be given and the history of the process (that is, the order in which various stress components are brought to act on the specimen and the way in which their magnitude is increased) will often influence the result.

The existence of a yield value can be detected, however, by any type of experiment which admits measurement of the non-recoverable deformation after unloading. If the deformations produced by loads below a certain threshold value appear to be completely recoverable, whereas permanent deformations appear only if this threshold is exceeded, the presence of a yield value is proved.

If the magnitude of the threshold value in simple shear is τ_f, a useful working hypothesis for more general stress systems is the following one. Suppose the state of stress to be described with reference to axes coinciding with the directions of the principal stresses and assume that the latter have the magnitudes σ_1, σ_2, σ_3. For many substances it seems certain that permanent deformations will appear as soon as

$$\tau_n = (1/3)\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2} > \tau_f \quad \ldots\ldots\ldots\ldots (1)$$

The quantity τ_n represents shear stress appearing in four systems of plane surfaces, parallel to the planes of a regular octahedron described with the directions of the principal stresses as axes; it is called octahedral stress in several of the papers presented. Likewise there can be calculated the shear in octahedral planes or octahedral shear, as defined by the expression

$$\gamma_n = (2/3)\sqrt{(\epsilon_1 - \epsilon_2)^2 + (\epsilon_2 - \epsilon_3)^2 + (\epsilon_3 - \epsilon_1)^2} \quad \ldots\ldots\ldots\ldots (2)$$

where ϵ_1, ϵ_2, ϵ_3 are the principal extensions.

It is then often assumed that the relation between shear stress and shear, or, as the case may be, between shear stress and rate of shear, as found in the simple shearing experiment, can be generalized into a relation between octahedral stress and octahedral shear (or, octahedral rate of shear). For instance, if the simple shearing experiment would have given a non-linear relation between rate of shear and shear stress of the form

$$\tau = \tau_0 (\dot{\gamma}/\dot{\gamma}_0)^m \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

$\dot{\gamma}$ being written for $d\gamma/dt$, while τ_0, $\dot{\gamma}_0$, and m are constants characteristic for the material, the more general relation would have the form

$$\tau_n = \tau_0 (\dot{\gamma}_n/\dot{\gamma}_0)^m \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Such an expression is given by Nadai, both in the paper mentioned before and in his paper presented here; γ here refers to the permanent deformation.

Institute of Technology,
Delft, Holland

DISCUSSION

Jean Goguel (Ecole des Mines, Paris, France)--Dans le cas des roches, un facteur qui n'intervient pas pour les métaux joue un rôle mécanique très important: c'est la pression propre du fluide qui remplit les pores. Un tel fluide existe dans toutes les roches superficielles, que ce soit de l'eau, de l'huile ou du gaz. L'eau d'imprégnation existe dans toutes les roches éruptives; il est vraisemblable qu'en profondeur, à haute température et haute pression, sa composition chimique doit varier, restant en équilibre avec les cristaux présents. Mais le rôle mécanique du fluide d'imprégnation ne dépends ni de sa composition, ni de son abondance. La charpente solide d'une roche ne supporte en réalité que la différence entre les contraintes extérieures et la pression hydrostatique propre du fluide d'imprégnation.

Cette considération est indispensable, entre autre, pour comprendre la rupture, tant dans les expériences sous triple étreinte (où, sauf avec un chemisage parfaitement efficace, la pression latérale s'exerce sur le fluide d'imprégnation) que dans la nature: les fissures planes, perpendiculaires à la direction de moindre pression, qui sont souvent indiquées par des veines de quartz, calcite, etc., ne résultent pas d'une simple traction, mais de ce que la pression du fluide dépassait la plus faible pression dans le solide. Il faudrait peuêtre faire intervenir ici, non pas la pression du fluide, mais la pression de cristallisation des cristaux susceptibles de se former à partir fluide, qui peut, dans certaines conditions de déséquilibre chimique, être sensiblement plus forte.

D'autre part, le fluide d'imprégnation joue un rôle en permettant, ou en facilitant, la recristallisation des minéraux de la roche, ce qui constitue un mécanisme de déformation très lente, important pour les déformations tectoniques de l'écorce, et qui doit jouer un rôle essentiel dans les déformations des zones profondes.

SOME MECHANICAL QUESTIONS ABOUT THE DEFORMATION OF ROCKS

A. Nadai

Much has been learned during the last 20 to 30 years through extensive experimental and theoretical investigations about the laws governing the plastic deformation and the fracture phenomena of the metals at normal and at elevated temperatures. Although natural rocks behave probably in many respects in a similar or analogous manner, the same may not be said of the ways in which rocks were deformed in the upper and deeper strata of the Earth. One of the most important factors which influences their slow mode of deformation is the time or duration of these processes as influenced through the increasing temperature with depth. From the data collected in the industrial laboratories it is known that even the strongest metals and alloys deform continuously with time at high temperatures, and creep under stress when the principal stresses are unequal. Attention has also been devoted by engineers to the fracture phenomena in metals as observed after long exposure to high temperatures and under continuous action of stress. From these observations it may be concluded that especially the fracture phenomena of natural rocks causing such effects as faulting and joints, and deep-focus earthquakes, must greatly and in a

definite way be influenced through the rising temperature with depths. It seems to this writer that one of the lesser understood phenomena in geophysics and encountered in the outer shell of the Earth is the creep and fracture of rocks as influenced by the rising temperature with depths, and an important question deserving careful experiments would be an investigation of certain types of rocks under conditions simulating their behavior, namely, under high mean pressures and at high temperatures.

The theory of strength by Otto Mohr suggested certain rules defining the orientation of the surfaces of macro-slip through a crystal aggregate which were based on the postulate of the existence of a "limiting curve" in a σ, τ plane (σ normal, τ shearing stress in the surface of slip) characterizing a material

$$(\sigma_1 - \sigma_3)/2 = F\,(\sigma_1 + \sigma_3)/2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

where $\sigma_1 > \sigma_2 > \sigma_3$ denote the principal stresses. Attention to the conditions to be satisfied in this limiting curve at its apex (where $\tau = 0$) has been called by LEON [1934], who pointed out that the radius of curvature of the limiting curve at the apex ($\tau = 0$) compared to the radii of the principal Mohr stress circles corresponding to simple uniaxial tension, compression, or a state of pure shear and their relative positions in the σ, τ plane has great significance in defining the orientation of the surfaces of fracture (whether of the cleavage or the shear type).

Whereas in recent geophysical investigations on slow deformation processes in rock strata an elastico-viscous material was postulated, it is known that the metallic materials at elevated temperatures do not creep according to a linear stress rate of permanent strain relation. If $\gamma_{oct} = \partial\gamma_{oct}/\partial t$ denotes the octahedral rate of creep and τ_{oct} the octahedral shearing stress, either a power function law

$$\tau_{oct} = \tau_o\,(\dot{\gamma}_{oct}/\dot{\gamma}_o)^m \qquad (0 < m \leq 1) \quad \ldots\ldots\ldots\ldots\ldots\ldots (6)$$

or the hyperbolic sine law

$$\dot{\gamma}_{oct} = \dot{\gamma}_o \sinh\,(\tau_{oct}/\tau_o) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

($\tau_o, \dot{\gamma}_o$ material constants) expresses their dependence at a given temperature [NADAI, 1937, p. 428]. Also a definite time has been observed to be required for causing fracture under a constant tensile stress σ even although the accumulated creep strains in many cases in metals may be of quite permissible small magnitude. For the time t at which glass fractures under a tensile stress σ at an absolute temperature T, TAYLOR [1947] proposed the expression

$$t = t_o e^{E\alpha/\sigma kT} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

(t_o, k, α constants).

A major problem in geophysics, it occurs, is the determination of the coefficient of viscosity

$$\phi = \partial\tau_{oct}/\partial\dot{\gamma}_{oct} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

in its dependence on the mean pressure $p = -(\sigma_1 + \sigma_2 + \sigma_3)/3$ and on the absolute temperature T - or on the actual depth under the surface of the Earth for various rocks.

Research Laboratories,
Westinghouse Electric Corporation,
East Pittsburgh, Pennsylvania

SOME EXPERIMENTS BEARING ON THE PLASTICITY OF ROCKS IN THE EARTH

David Griggs

Plastic properties have been observed in normally brittle rocks under the following conditions: (1) Short-duration uniaxial compression and extension experiments under high confining pressure, both jacketed and in contact with a pressure fluid. (2) Long-duration creep tests at

room temperature, dry, no confining pressure. (3) Creep tests in the presence of solvents. (4) Creep tests at high confining pressure, room temperature. (5) Short-term compression tests at high confining pressure, in the presence of water, at elevated temperature.

The observed behavior of rocks which are rendered plastic by these conditions of testing is in all respects consistent with that of metals and some other solids, which has been so aptly summarized by Burgers. No phenomena peculiar to rocks or rock-forming minerals have been observed to date. Interest then centers on how well determined are the plastic constants of rocks in laboratory experiments of the type mentioned above; how far these experiments go toward duplicating conditions in the Earth; and whether our knowledge of the plastic behavior of solids in general is sufficient to allow confident extrapolation from laboratory observations to plasticity in the Earth.

It may be said briefly that plasticity has been studied quantitatively in only a few of the more easily deformed rocks of sedimentary origin such as marble and alabaster. The rocks believed to be typical of the Earth below its superficial sedimentary cover have not yet been made to flow plastically under conditions which permit quantitative measurements of plastic constants. Environmental conditions available in current laboratory practice can duplicate conditions of pressure, temperature, and solutions, in the Earth only to a depth of about ten kilometers--about one-third the thickness of the continental crust. Even here it is difficult to cope with the low rates of flow typical of Earth deformation. One can say with assurance that the next ten years will not produce laboratory experiments in which the plastic properties of important rock types and minerals will have been completely determined over environmental conditions found throughout the crust. Conditions in the Earth's mantle--say to depths of 700 km, where deep-focus earthquakes occur--are outside the present range of controlled laboratory experiments, with the exception of Bridgman's "shearing" apparatus, the results of which have so far not been adequately connected with normal plastic behavior.

It remains to be seen then whether knowledge of plastic behavior of solids in general is sufficient to warrant extrapolation of our meager knowledge to conditions deep in the Earth. The writer feels this is a great contribution which might be made by our colleagues in Theoretical and Applied Mechanics, and hopes that the Hershey Conference will have provided stimulus for efforts in this direction.

As illustrations of some phenomena which have been observed in rocks by the writer, a few examples are given in Appendix 1. These are not to be construed as indicative of actual behavior of rocks in the Earth, but are perhaps steps in that direction.

Present work in this field by the writer and his colleagues has been aided by a grant from Office of Naval Research.

Appendix 1--Some Illustrative Plastic Phenomena of Rocks in Laboratory Experiments

Behavior under high confining pressure at room temperature--The principal effect of high confining pressure is to increase the ductility of rocks and other solids. At something like 3000 bars confining pressure, limestone and marble become appreciably plastic, and at 10,000 bars, have been elongated and shortened in excess of 40 pct without fracture. Jacketed specimens are much less subject to fracture than unjacketed ones in the intermediate pressure range. Jacketed specimens follow Mohr's construction while unjacketed ones do not.

Work-hardening is pronounced in limestone or marble plastically deformed, and the degree of work-hardening increases with confining pressure. The Bauschinger effect is uniformly observed. Elastic-afterworking is found in all highly deformed specimens.

Most rock-forming minerals have been observed to become plastic at sufficiently high confining pressure. For example, Bridgman has deformed sapphire at 25,000 bars. An exception is quartz, which behaves like a brittle solid up to about 30,000 bars in Bridgman's experiments, exhibiting no plastic flow. Creep is pronounced in unjacketed limestone at 10,000 bars confining pressure for stresses above the yield point, resembling creep in metals near the melting point. Creep in jacketed marble at 10,000 bars appears to be recoverable.

The mechanism of deformation of calcite marble has been shown to be predominantly twin--and translation gliding on the $\{01\bar{1}2\}$ crystal planes of calcite. The law of maximum resolved shear stress has been shown to apply for single crystals, and Taylor's hypothesis of deformation of the aggregate is consistent with observations.

Behavior of limestone in creep with no confining pressure, room temperature--A single creep test on Solenhofen limestone lasting 11 years showed a minimum equivalent viscosity of 10^{22} poises at a compressive stress of 1400 kg/cm^2. All the measured deformation (totaling 0.02 per cent in 11 years) may have been recoverable flow.

Flow under conditions favoring recrystallization--Alabaster, immersed in water at room temperature and pressure, and tested at constant compressive load varying from 100 to 300 kg/cm^2 showed creep characteristic of metals. The constant velocity component follows the hyperbolic sine law used for metals. Added confining pressure of 1000 bars increased the rate of creep as predicted thermodynamically. The maximum duration of the experiments was 5.5 years. All experiments ultimately terminated in fracture.

Quartz aggregates become very deformable under conditions favoring recrystallization and the strength of the single crystal is indeterminate, since any stress applied produced fracture if maintained long enough. At 1000 bars pressure and 400° C in water vapor, quartz is mobile under applied shearing stress. The mechanism of deformation is uncertain, but solution and redeposition clearly occur, and high degrees of preferred orientations are produced in the case of high shearing strains.

Marble deforms much more readily under conditions favoring recrystallization. This is discussed in the next section.

Deformation of marble at 10,000 bars confining pressure with varying temperature and solvents--A series of experiments is now in progress on homogeneous Yule marble. The confining pressure has been kept constant at 10,000 bars. One series of experiments has been performed dry and at room temperature, a second series dry at about 150° C, and a third series at 150° C in the presence of water. The rate of deformation is the same in all experiments. Correlated experiments on calcite single cyrstals have been performed.

The dry, room-temperature experiments have provided evidence favoring Taylor's hypothesis of deformation of granular aggregates, functioning in this case principally through the known twinning and translation in the calcite crystals. This permits correlation of the anistropic properties of the original marble. The dry, 150° C experiments show a similar correlation (tentative) but with much reduced strength (that is, stress at given strain). Single crystal experiments show that the shear stress for translation is reduced proportionately more by the elevated temperature (about a factor of four) than is the shear stress for twinning. The average reduction of strength for the marble aggregate is about 35 pct, and is believed to be consistent with the above interpretation.

The addition of 0.5 pct water by weight lowers the strength of the marble further by about a factor of two. Preliminary examination shows no qualitative differences in the mechanism of deformation. Creep has been explored but non-recoverable flow is small at constant stresses well above the yield stress.

The considerable effect on strength of marble due to change in temperature of only 120° C and the addition of water, which is not predicted by theory, so far as the writer knows, may serve as a caution to anyone attempting to extrapolate laboratory experience to the widely different conditions in the Earth.

This is drawn from unpublished material of the writer, F. J. Turner, C. S. Ch'ih, W. M. Miller, J. W. Handin, and J. Sosoka.

University of California,
Los Angeles, California

DISCUSSION

The paper by Griggs was followed by a discussion on various forms of failure (flow or fracture). In particular, Birch spoke of some current investigations by E. C. Robertson concerning the boundaries between different types of failure. In one set of experiments, hollow cylinders of limestone, sealed off with steel end pieces and rubber tubing, were caused to fail by the application of hydrostatic pressure over the external surface, the internal pressure being zero. Thin-walled cylinders failed by brittle fracture on a helical surface of maximum shearing stress. Thick-walled cylinders showed no external failure, but were reduced in external diameter by a combination of flow and

flaking at the internal surface, which tended to fill the interior with small fragments. With Solenhofen limestone, the transition from brittle failure to flow for this type of experiment takes place at an external pressure of about 3000 atmospheres and a ratio of external to internal diameters of about three.

CRUSTAL STRAIN CHARACTERISTICS DERIVED FROM EARTHQUAKE SEQUENCES

Hugo Benioff

A procedure has been devised for determining the relative size of elastic strain-rebound increments from earthquake magnitudes [BENIOFF, 1949, 1951]. A plot against time of the accumulated sum of such increments for a given sequence of earthquakes provides information as to the strain characteristics of rocks as well as the strain-time relation of the system which generates the sequences. In this procedure it is assumed that earthquakes are produced by elastic rebound of strained rocks, in accordance with Reid's theory. If an average elastic strain ϵ_1 preceding an earthquake is assumed to be distributed uniformly throughout an effective volume V of the fault rock, the strain energy in ergs stored in the rock is given by

$$E = \mu V \epsilon_1^2/2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (10)$$

where μ is the appropriate elastic constant of the rock. When the fault slips to produce the earthquake, a fraction p of the stored elastic energy is converted into seismic waves. Thus if J is the energy in ergs of the waves

$$J = p \mu V \epsilon_1^2/2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (11)$$

For a given fault μ and V are constants. Moreover, it is reasonable to assume that p is also constant. Hence Eq. (11) may be written

$$J = C^2 \epsilon_1^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (12)$$

where C is a constant such that $C^2 = p \mu V/2$. If the strain is reduced to zero during the earthquake, the stored elastic strain is equal to the strain rebound, that is

$$\epsilon_1 = \epsilon$$

Hence

$$J = C^2 \epsilon^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (13)$$

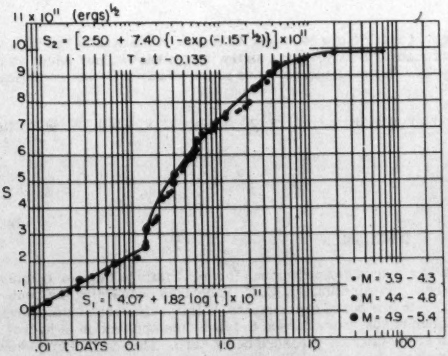


Fig. 4--Long Beach aftershock sequence

Taking the square root of Eq. (13)

$$J^{0.5} = C\epsilon \quad \ldots\ldots \quad (14)$$

Thus on a given fault the square root of the energy of an earthquake is proportional to the elastic strain-rebound increment which generates it. If S is the accumulated sum of the values $J^{0.5}$ for a sequence of earthquakes derived from a single fault, a graph of the relation of S to time represents the strain relief (multiplied by C) as a function of time. Values for $J^{0.5}$ may be derived from Richter's instrumental magnitude M by means of the following preliminary equation of GUTENBERG and RICHTER [1942]

$$\log J^{0.5} = 6.0 + 0.9\,M \ldots \quad (15)$$

Aftershock sequences--Figure 4 is a graph of the strain-rebound characteristic of the aftershock sequence

of the Long Beach earthquake (March 10, 1933; $\phi = 33° 34.5' N$, $\lambda = 117° 59' W$) plotted on a semi-logarithmic paper. The value of S for each aftershock is represented by a dot having a diameter related to the magnitude as shown in the legend on the figure. Note that the dots fall on two distinct curves. The first begins with the first aftershock at t = 0.007 and continues to t = 0.15, where t is the elapsed time in days from the origin time of the principal earthquake. This curve is calculated from the equation for S_1 as shown in Figure 4 and is of the form given by GRIGGS [1939] for rocks and by others for other materials for compressional elastic or recoverable creep strain. Since the signs of the increments of S are indeterminate, it is impossible from these measurements alone to distinguish between forward creep in response to applied stress or creep recovery following removal of stress. In accordance with a proposed theory of aftershocks [BENIOFF, 1951], it is assumed that the movement is one of recovery. The second phase in the sequence began at t = 0.15 and continued to t = 70 days approximately. The second curve in Figure 4 was calculated from the equation for S_2 as shown and is of the form derived empirically by MICHELSON [1917, 1920] for shearing creep recovery. The origin of the aftershock sequence of the Long Beach earthquake may therefore be attributed to elastic afterworking of the fault rock. The afterworking began as a compressional creep strain recovery followed after an interval of 0.135 day by a shearing creep strain recovery. That there would be both compressional and shearing creep effects is not unexpected but the delay in onset of the shearing strain recovery is surprising. Since in the creep range of deformation the stress-strain relationships are not linear, it is possible that the compressional and shearing creep strains may interact with each other in such a way that the frictional component of the shearing creep mechanism may be increased to the point of locking by action of the compressional creep stress. (Creep strains assumed in this paper refer to time-dependent strains.) BRIDGMAN's [1949] discovery of an anomalous volume change in rocks subjected to simple compression in the creep range of stress provides the basis for a possible mechanical explanation of the interaction between compressive and shearing creep strain. He found that up to a limiting value of compressive stress, the length and volume both decrease with increasing stress increments in accordance with ordinary experience. For stresses beyond this limit, the length continues to decrease but the volume increases sharply. Moreover, a substantial portion of this volume increase is recoverable upon release of stress. Thus during the initial stages of release, the volume decreases. Such an anomalous behavior must involve significant changes in the internal structural configuration of the material and so exert an appreciable effect on the shearing deformational behavior. The increased pressure and the changes in structure may both conspire to lock the shearing strain until the compressive stress decreases to the value where volume changes become normal. Just before the principal earthquake the ratio of recoverable creep strain which produced the aftershocks to the elastic strain which produced the principal earthquake was approximately 2.2 [BENIOFF, 1951]. However, only about six per cent of the energy stored in the creep mechanism appeared as seismic waves. The rest was dissipated as heat in the rock during 20 days of aftershock activity.

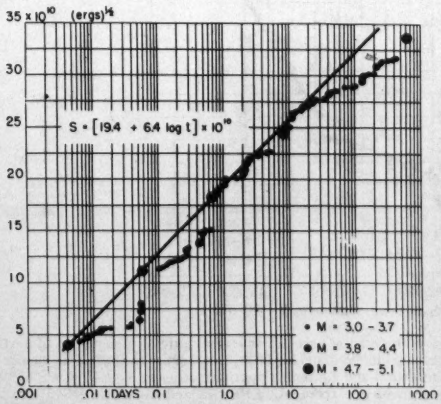


Fig. 5--Manix earthquake aftershock sequence

In Figure 5 is shown the strain-rebound characteristic of the aftershock sequence of the Manix, California, earthquake of April 10, 1947 ($\phi = 34° 58' N$, $\lambda = 116° 32' W$, magnitude 6.2). The straight line is calculated from the equation shown on the figure and represents compressional elastic (or recoverable) creep strain. The departure from the straight line after approximately 100 days represents either unrecoverable flow of the rock in the long intervals between shocks or permanent cementing or locking of portions of the fault. Other sequences studied have exhibited compressional, shearing, or combined compressional and shearing types of creep movement. In the sequences having compressional deformation only, activity was followed for intervals varying from 100 days minimum to 600 days maximum. On the other hand, sequences having shearing type of creep came to early definite terminations in intervals varying from one to 500 days.

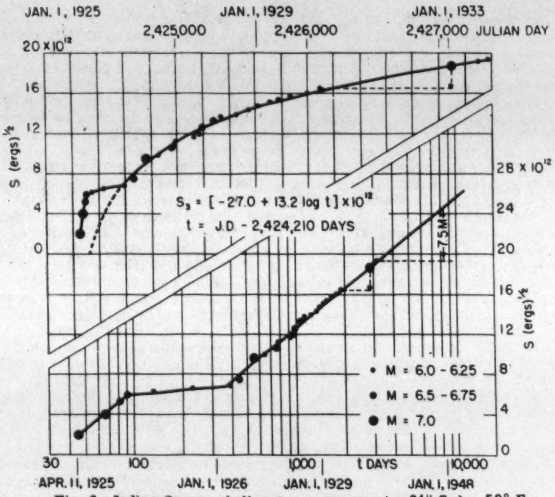


Fig. 6--Indian Ocean, shallow focus swarm; $\phi = 34^{\circ}$ S, $\lambda = 58^{\circ}$ E

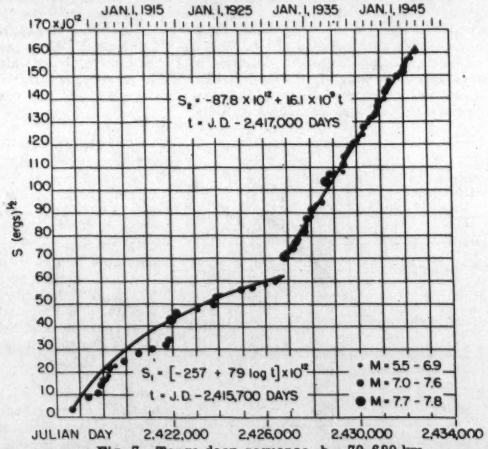


Fig. 7--Tonga deep sequence, h = 70-680 km

Earthquake sequences--Figure 6 is the strain-rebound characteristic of a sequence of earthquakes which occurred from April 11, 1925 to October 23, 1933, in a region in the Indian Ocean not more than a few square degrees in extent and centering approximately at $\phi = 34^{\circ}$ S, $\lambda = 58^{\circ}$ E. The data for this and the following sequences are from GUTENBERG and RICHTER [1949]. In the upper portion of Figure 6, the characteristic is plotted with arithmetic coordinates and in the lower it is plotted with semi-logarithmic coordinates. The characteristic represents a compressional

elastic (recoverable) creep. The sign of the creep is indeterminate so that it can be either forward deformation or afterworking. The break in the curve between 90 and 400 days may be interpreted as an interval during which the fault surfaces slipped without producing earthquakes. After the shock of April 28, 1930, the fault surface apparently became locked so that no earthquakes were produced for an interval of approximately three years. During this time the strain continued to accumulate and when the fault finally gave way, it produced two shocks which brought the rebound value S up to that determined by the curve. If, since the last shock of the series, the strain has been accumulating in accordance with the curve there should now be stored enough energy for a shock of greater than 7.5 magnitude.

Figure 7 is a plot of the strain-rebound characteristic of all of the deep-focus earthquakes (h = 70-680 km) of the Tonga-Kermadec sequence [BENIOFF, 1949]. The characteristic is made up of two phases. The first phase beginning April 1, 1907, and ending October 18, 1931, has the form of a compressional elastic creep. Beginning with the great earthquake of May 26, 1932, the second phase follows a linear pattern with respect to time. Assuming that the strain-generating stress was constant, the dual nature of the characteristic can be interpreted as indicating a strong locking of the great fault blocks at one particular point during the first 25 years. The resulting logarithmic pattern of the sequence during this interval exhibits the elastic (or recoverable) creep compression of the fault rocks. The earthquake of May 26, 1932, represents the breaking of the locking point of the fault so that thereafter the blocks moved linearly with respect to time. The fact that the equation for the curve in the first phase does not contain a term proportional to the time indicates that although the layer in which this sequence originates extends to a depth of nearly 700 km, the rock was able to maintain a recoverable strain without appreciable flow for 24 years. The length of the active fault structure is 2500 km.

Figure 8 is a graph of a strain-rebound characteristic of a deep-focus sequence (h = 550-660 km) for South America [BENIOFF, 1949] plotted with arithmetic coordinates. This graph takes the form of intersecting straight lines from which it may be inferred that the fault blocks moved with constant velocities. From the date at which observations began April 28, 1911, until January 17, 1922, the block velocity was large and the earthquakes which determined it were large. Following January 17, 1922, the earthquake frequency increased somewhat while the magnitudes decreased sufficiently to reduce the block velocity to 1/5 of its initial value. In the initial phase, the fault locked strongly following the fourth earthquake and no additional earthquakes occurred for 5.5 years. During this interval the strain continued to accumulate at the initial constant rate so that when the fault did give way it generated two great earthquakes which brought the total movement to the value determined by the initial rate. Thus the rock of this fault situated at a depth of 650 km maintained a linear elastic strain without observable creep for a period of 5.5 years. The origin of the discontinuity in rate which took place in 1922 is obscure. Such discontinuities have been observed in other sequences.

The elastic strain-rebound characteristic of the sequence of intermediate depth (h = 70-300 km) earthquakes of South America [BENIOFF, 1949] is shown in Figure 9 drawn with semi-logarithmic coordinates. The graph takes the form of two straight lines and represents movements in which the rates increase exponentially with the time. If the generating stresses are constant, the movements are of the type of creep which is characteristic of substances having temperatures in the annealing range above the strain hardening limit [TIMOSHENKO, 1941] and may be defined as plastic flow. This sequence exhibits a discontinuity in rate at about the same date when the deep sequence changed rate.

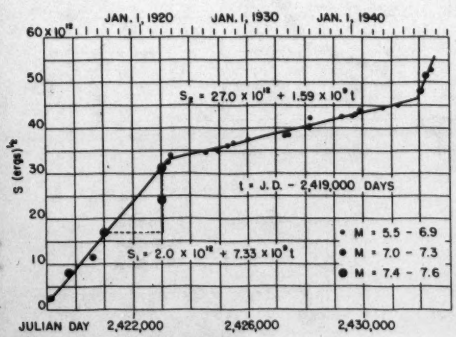


Fig. 8--South American Deep sequence, h = 550-660 km

World sequences [BENIOFF, 1951]--Figure 10 is a graph of the strain-rebound characteristic of the sequence of all earthquakes of the world having magnitudes equal or greater than 8.0, which have occurred since 1904. Although the shocks of this sequence represent many differ-

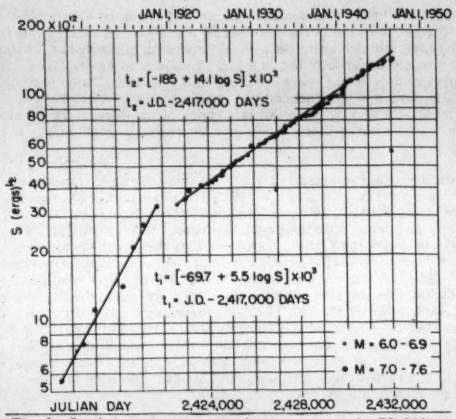


Fig. 9--South American intermediate sequence, h = 70-300 km

ent faults having presumably different values of μ and V, the singular nature and regularity of the curve indicates that μ and V or the product μV must be substantially the same for all earthquakes in this magnitude range. In this graph each black rectangle represents the elastic strain-rebound increment associated with a particular earthquake of the sequence. The heights of the rectangles are related to the earthquake magnitudes as shown in the legend on the figure. The characteristic has an approximately saw-tooth shape with amplitudes and periods decreasing linearly with the time. The initial points A, B, C, and D of the active intervals mark the times when the accumulated world strain was maximum. The end points a, b, c, d, e, and f mark the times at which the accumulated world strain passed through minima. The upper dashed line drawn through the points of minimum strain should therefore represent the total secular strain-generation (times the constant C) of the system. The small spread of points on this line indicates that the rate of strain-generation has been very constant since 1907. Since during the active intervals the average strain-release segment is very nearly linear, it may be concluded that earthquakes in this magnitude range are not independent events, in that release of strain by one shock

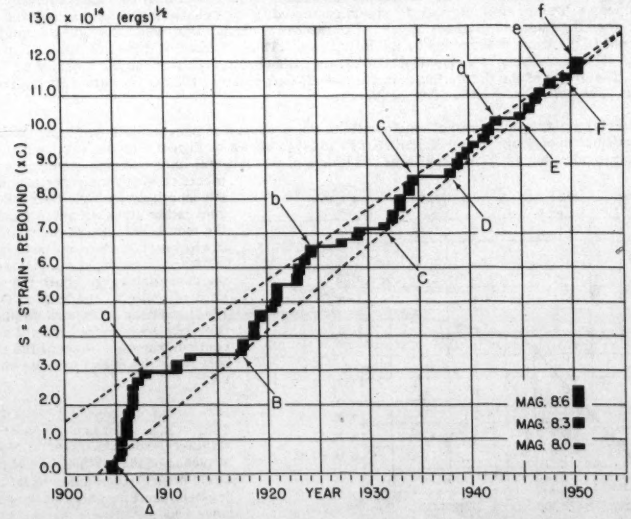


Fig. 10--Elastic strain-rebound characteristic; sequence of world shallow earthquakes, magnitudes ≥ 8.0, since 1904

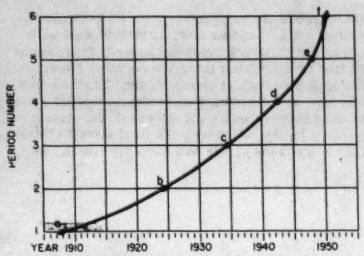


Fig. 11--Terminal dates of active periods in the sequence of world shallow earthquakes, magnitudes ≥ 8.0

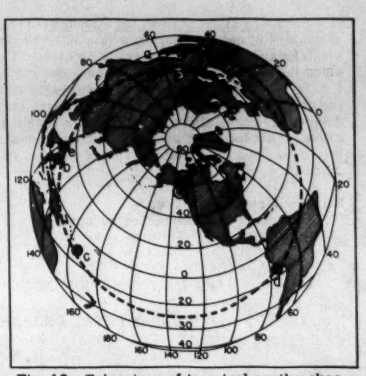


Fig. 12--Epicenters of terminal earthquakes

affects the time and presumably the amount of strain release of subsequent shocks. In order to explain the alternating intervals of activity and quiescence it is necessary to assume that there exists a world-wide mechanism which locks all faults simultaneously--possibly through variations in the normal stress on the fault surfaces. Thus, although global strain is being generated at a constant rate given by the slope of the upper dotted line in Figure 10, it is released only during intervals when the fault-locking is reduced. Figure 11 is a plot of the origin times of the terminating earthquakes of each active interval. The letters a, b, c, etc., refer to the corresponding earthquakes in Figure 10. It would appear from this curve that the earthquake of August 15, 1950, not only marks the end of the active period with which it is associated but also the end of a secular cycle of activity which began in 1904 or earlier.

In Figure 12 the epicenters of the terminating earthquakes are plotted on a world map. They fall very nearly on the dashed circle shown. This circle is very nearly a great circle and hence it defines a plane passing through the center of the Earth. The pole of the circle is approximately situated at $\phi = 55°$ N, $\lambda = 127°$ W, and is indicated by two concentric small circles in the figure. Since there are only six shocks in this figure, the fact that they appear to define a plane may of course be an accident only. Nevertheless, the figure is shown here since it may have significance. The earthquakes are marked in accordance with Figures 10 and 11.

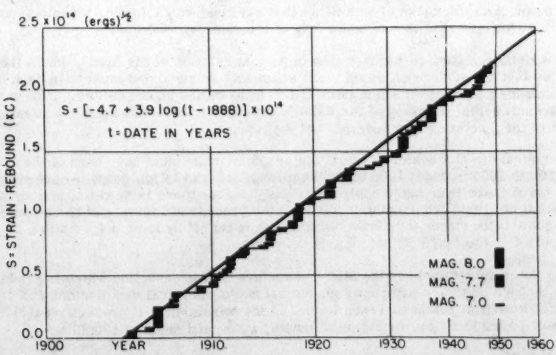


Fig. 13--Elastic strain-rebound characteristic; sequence of world deep earthquakes, magnitudes ≥ 7.0, depth = 300-650 km

Sequence of great deep earthquakes--The strain-rebound characteristic on all great (magnitude ≥ 7.0) deep earthquakes (h = 300-680 km) since 1904 is shown in Figure 13 plotted with semi-logarithmic coordinates. It is evident that the rate of strain release has been decreasing since the beginning of the sequence. The straight line is calculated from the equation shown in Figure 13. It may represent a compressional elastic (recoverable) creep strain. The fact that the observed points fit a logarithmic curve so well may be interpreted as evidence that all great deep earthquakes also are related in a single stress system in which a compressional elastic creep strain has been accumulating or releasing (since 1888). Whatever the final interpretation, the curve does show that the rate of release of elastic-rebound strain has been decreasing as $1/t$ since 1904.

Seismological Laboratory,
California Institute of Technology,
Pasadena, California

PART II - FORMATION OF FOLDED BELTS AND GEOSYNCLINES

FUNDAMENTAL PROPERTIES OF OROGENIC BELTS

W. H. Bucher

The most conspicuous and perhaps also the most significant structural features of the face of the Earth are the great belts of folded mountains, like those of the Himalayas, the Andes, the Urals, and the Appalachians, the so-called orogenic belts. Along these long and relatively narrow zones, great thicknesses of dominantly marine sediments have been squeezed together and thrust one upon the other to form highly elongated folds with axes essentially parallel to that of the belt. In every case, along a strip which lies generally near one side of the belt, the original sediments have been altered profoundly (metamorphosed) by increased heat and chemical changes that involve the introduction and removal of relatively small amounts of substances. During deformation and metamorphism, and, for some time thereafter, quantities of relatively mobile intrusive rock materials, the so-called plutonic rocks, have made their appearance in and near the zone of metamorphism, making room for themselves much as rock salt does when it rises through tens of thousands of feet of rock into overlying sediments to form salt anticlines. Most of these were wholly or at least partly (interstitially) in the molten state.

To be valid, any theory concerning the physics of the Earth must account for the properties of the orogenic belts. It is pertinent, therefore, to set forth briefly what their fundamental properties appear to be, reduced to the most general terms from the confusing complexity of geological reality.

(1) The original thickness of sediments that have undergone folding within an orogenic belt is several times greater than that of sediments of the same age outside.

James Hall, who first recognized this important relation in the Appalachians (1857), saw that this implies that the surface on which these sediments accumulated must have been bent down to form an elongated depression which later (1873) Dana called a geosyncline. This is recognized today as a fundamental property of the Earth's crust, that the first step in the creation of an orogenic belt is the formation of a geosynclinal depression.

The original dimensions of a typical major geosyncline must have been of the order of magnitude of 100 to 200 km wide, 1000 to 2000 km long, and 4 to 12 km deep. At present these figures cannot be much more than vague approximations, because there is as yet no way by which the actual amount of crustal shortening involved in the process of folding can be computed, and because orogenic belts either terminate abruptly, as if cut off by later deformation, or join others in such a way that the length is not clearly definable.

The most useful example is the still undeformed Gulf geosyncline which is gradually becoming known through intensive and costly geological and geophysical explorations and drilling operations. Extending from southern Texas to east of the Mississippi, it presents roughly the following dimensions: 1000:200:10 km; or ratios of length, width, and depth of 100:20:1.

(2) The Gulf geosyncline deserves special attention because it has reached great depth without being accompanied by a corresponding upwarp. This seems indeed to be a second fundamental

property of typical major orogenic belts: In the first stage of their development, no upwarp of comparable dimensions, no "geanticlinal" bulge, rises alongside the geosynclines.

This conclusion is borne out by the nature of the sediments of the orogenic belts. Quite generally, the earlier sediments consist of fine-grained shales and silts or fine-grained limestones and cherts, such as form from calcareous and siliceous oozes. After thousands of feet have accumulated, coarser materials appear such as sandstones and graywackes leading to the deposition of thick conglomerates, that is, great piles of pebbles and boulders derived from mountain chains rising alongside of and within the geosynclines.

This contrast between the earlier geosynclinal and later orogenic phases of sedimentation in the mother-geosynclines of folded belts led some geologists, including the writer, to look to tensional stresses in the crust for an explanation of the initial geosynclines in contrast with the later compression that produced the folding. The more the writer learned about the complex realities of the structure of the continents, the more he realized that the concept of world-wide tension, for which he once believed to have good evidence, is untenable [BUCHER, 1933, 1939].

All available evidence proves that, under deformation, the outer part of the Earth's crust behaves plastically, that is, in such a manner that at points where it yields under tangential pressure it should thicken. It seemed paradoxical to find belts of orogenic folding in such a shell start out with downward bending. VENING MEINESZ [1950] has recently pointed to reasoning according to which, if valid, such behavior in a weak, plastic shell is not only possible but inevitable. An initial relatively slight upward thickening leads to prolonged downbending and the formation of a geosyncline, with all further thickening of the crust taking place radially downward, until failure of the crust initiates the folding and thrusting of the orogenic phase. With reasonable assumptions concerning the dimensions involved, Vening Meinesz's theory yields results of the right order of magnitude. It may well represent a major step toward the solution of the problem of orogenesis.

(3) A third property of orogenic belts is best seen where they change direction repeatedly. In such a case, the geological record shows that deformation has proceeded essentially at the same time along the whole length of a curving belt, irrespective of its trend. In Europe, for example, the young Alpine orogenic belt surrounds the Po valley on three sides, trending first northwest in the northern Apennines, then west and swinging through 180° in the western Alps back to the east-west direction over a total length of about 1000 km. Not much more than 100 km separate the northern and southern east-west trending stretches of the curve. Emerging from the plains northeast of Vienna, the Carpathian branch of the Alpine system trends first northeast, then east and southeast; then in the Transylvanian Alps, it turns sharply, runs westward for 400 km, only to turn abruptly at the Iron Gates of the Danube through 180° into the Balkan Mountains. Along this series of curves, the orogenic belt measures about 2000 km in length, and the distance that separates the east-west portions of the belt north and south of the Danube is 200 km.

In southeastern Asia, the great hairpin curve of the Carpathian-Balkan orogenic belt has its counterpart, on a still vaster scale, in that of the island arc that curves through 180° around the Banda Sea. Here the distance that separates the east-west branches of the curve measures more than 400 km. And this is only a detail in the gigantic loop, in which the young orogenic belt of southeastern Asia swings from its southerly trend in Burma through the great east-west arc of the Sunda Islands back into the south-north direction of the Moluccas and eastern Philippine Islands. A distance of 2000 km separates the inner borders of this less regular and more complicated loop of 10,000 km length.

In all these cases, from the smallest to the largest, the fold axes lie essentially parallel to those of the belts themselves. Everywhere, therefore, the stresses responsible for the deformation must have acted at right angles to the belts, from point to point around the curves.

If, for instance, the formation and folding of the Burma-Sunda-Philippine arc were the result of a uniform movement of the land mass comprised within it toward the south-southeast, as is suggested by the arrows on a map of VENING MEINESZ [1950, opposite p. 44], the folds in Burma should be aligned en echelon, that is, in short folds, each with southeast-trending axis, strung along in a north-south belt. Instead, the geological structure lines as well as the zone of negative anomalies follow the trend of the whole belt faithfully.

Whatever may be the reason for the strange deflections of these and other orogenic belts, they seem to prove that the folds within and along them came into being under all-sided horizontal pressure in the crust. This conclusion assumes greater importance in the light of another fundamental property.

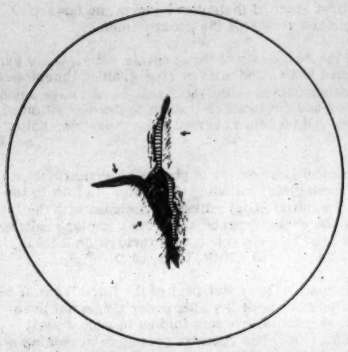


Fig. 14--Thin spherical shell of paraffin fractured under compression

(4) The orogenic belts that have come into being since the beginning of Carboniferous time are not scattered at random, but are aligned in a few well-defined bands that extend into every octant of the Earth's surface. If the inference drawn in the preceding discussion is correct, then tangential compression must be present throughout the Earth's crust. In this pattern, the central region of Southwest Asia, from the Hindu Kush Mountains to the Kirghiz Steppe, stands out. It is a focal region toward which several great orogenic belts converge: from the southeast, the great ranges that culminate in the Himalayas; from the north, the once great belt of the Urals; and from the west, the Alpine-Iranian belt.

An equally unique area dominates the opposite side of the globe: the almost continuous band of orogenic belts which surrounds the many-angled calotte of the Pacific Ocean [STILLE, 1944].

The writer considers it possible that this peculiar asymmetry in the pattern of orogenic belts goes back directly to the manner in which a fairly strong plastic shell fails under compression. The writer bases this opinion on the failure, under compression, of a relatively thin, weak shell which he observed in the laboratory many years ago. A thin, hollow paraffin shell, made by coating the inside of a spherical Christmas ornament, was suspended in warm water in a cylinder by means of a hairnet and subjected to hydraulic pressure. Failure took place along three oblique shear planes starting from a point as shown in Figure 14 [BUCHER, 1924]. (Note that the gap shown in the figure is due to the spreading that followed release of pressure. This made visible the inclined striated shear planes which dip toward the arrows indicating the direction of overriding movement. The writer is now setting up better equipment to extend these observations.) Along each one of the shear planes, the weak paraffin bent and rolled over as one side moved over the other.

Even though this experiment was far from being dimensionally correct, it shows that within certain limits of the factors involved, crustal failure will introduce a polarity into the deformation pattern. The point from which the initial shear planes radiate may be assumed to be the experimental counterpart of the focal area in southwestern Asia. In any but an ideally homogeneous sphere, the lines of yielding must be deflected as they grow beyond the initial stage seen in the experiment, with the result that they would come to surround a large, irregular portion of the shell on the opposite side of the sphere. On the Earth, this would correspond to the Pacific region. If it is true that the growth stages of an orogenic belt are produced by tangential pressure, and if the pattern of these belts implies that all-sided tangential pressure prevails at the same time at all points throughout the crust, then this possible explanation of the peculiar polarity in the patterns of orogenic belts deserves attention.

(5) The preceding discussion is based on the orogenic belts of the last 3×10^8 years, that is, of something like one-seventh of recorded geologic history and perhaps one-tenth of the Earth's age. This is necessary because orogenic belts are not original elements of the Earth's crust, but secondary features that come into existence at different times, are active for various lengths of time, and then cease to function, while new ones arise, some in close relation to earlier ones, others quite independently. They are the lines of yielding which relieve the areas between them from the pressures that are needed to produce yielding and failure. In such an arrangement, yielding along one belt causes a redistribution of tangential pressures across the adjoining areas in such a way that at any given point the pressure will fluctuate with time, dropping below the value required to produce further deformation, whenever yielding somewhere else makes this possible. Sooner or later, any given orogenic belt may thus cease to function. Such local relief of pressure explains another important property of orogenic belts.

(6) The great elevation above sea level, which is characteristic of all young orogenic belts, is the result of later vertical uplift and not of the process of folding and thrusting under tangential stress. Geophysicists and geologists see in this property evidence of local isostatic adjustment of

the thickened crust after release from the pressure that produced the orogenic deformation. The uplift brings metamorphosed regions to sufficient elevations that erosion can expose them.

Detailed structural analysis of the oldest parts of the continents shows that even the earliest Pre-Cambrian terranes consist of metamorphosed lower parts of former orogenic belts that, like all others, began as geosynclines.

The more the intrusives, the granites, and related silica-rich rocks of these metamorphic belts are studied, the more there is reason to doubt that they are derived from a primordial light, acid crust. It looks more and more as if granites were a by-product of metamorphism and orogeny, as if they were "made" when a geosyncline enters the orogenic stage, rather than "remade" from the material of an "original" sialic outer-crustal layer. If that should prove to be true, then the sialic parts of the Earth's crust would be both light and high, because they consist of old orogenic belts that have reached isostatic equilibrium long ago and have been reduced to lowlands by erosion. Basalt would have to be thought of as the original material of the outer part of the Earth's crust and the ocean floors as those parts of the Earth's surface that have so far fortuitously escaped orogenic deformation [BUCHER, 1950]. The young mountain ranges which stand on the floor of the deep sea, almost completely concealed in water, and by their gravity anomalies and accompanying belts of intermediate and deep earthquakes betray their true orogenic nature, should hold the final clue to the understanding of the questions raised by this outlook. The greatest of these, the submarine mountain belt that extends southward across the western Pacific from Japan through the Bonins and Marianas to Palau, a range comparable in length and height to the Himalayas, deserves special attention [HESS, 1948]. Here modern geophysical tests, detailed geological field work and deep drilling should bring decisive results.

The preceding comments have led beyond the scope of this paper into the realm of geological hypothesis. The geophysicist concerned with the mechanics of the Earth's crust will do well to take cognizance of the recent trend in geological thinking, which, by the way, goes back in its beginnings over a century [WEGMANN, 1950]. Our minds must be kept open for possibly rather radical changes in outlook.

One thought runs through all the considerations presented above: Tangential compression dominates the whole record of Earth deformation. Those who believe that subcrustal convection currents account for mountain folding must explain the many conflicts between their hypothesis and the properties of orogenic belts set forth in the preceding pages. To mention three: (1) The continuity of orogenic belts through thousands of kilometers; (2) the great differences in the radii of curvature along their often tortuous courses; (3) the fact that practically everywhere the axes of individual folds are parallel to that of the belt itself, proving that the stresses responsible for the deformation were directed at right angles to the belt. To these must be added another not as yet stated explicitly: Every shortening produced by the drag of a subcrustal current in an inert crust must correspond to stretching elsewhere. No evidence of such stretching is recognizable where the inside of great curves lies on land as, for example, inside of the great arc of the Carpathians; in the upper Po valley; in the plains of Wallachia; and, above all, in the mountain lands of southeastern Asia, within the greatest of all the sharp curves referred to above. Until these objections are met, the writer sees no escape from the conclusion that throughout recorded geological history, the Earth's crust has been under tangential compression.

Geophysicists who cannot accept crustal shortening and believe the Earth to be expanding, must find a way to make the crust expand faster; or if they prefer to assume the Earth's dimensions to have remained essentially constant, must show ways of enlarging the crust continually or intermittently to account for the ever-repeated failure under compression.

From this discussion, the element of time has been largely omitted. To be definite enough to be critically evaluated, any general statement about it would require more space than would be justified here. Fortunately, the properties of geosynclinal belts presented in these pages are valid without relation to timing.

In this paper, comments expressing the writer's opinions have been added to the factual statements in the hope that he will be set right where his reasoning has gone astray, and that he may contribute to the reexamination of current ideas which was the prime purpose of this conference.

Columbia University,
New York, New York

ON THE ORIGIN OF GEOSYNCLINES, MOUNTAIN FORMATION, AND VOLCANISM

P. P. Bijlaard

The creation of geosynclines, the formation of mountains, and volcanism may be explained by the writer's theory of local plastic deformations [BIJLAARD, 1935, 1936a]. In the deeper layers of the Earth's crust the high initial hydrostatic pressures prevent the origin of cracks, so that, after superposition of tangential compressive stresses, permanent deformations will occur by shearing within the crystallites. Hence, in analogy to metals, the plastic deformations are governed by the resolved shear stress in the slip planes and thus by the elastic shearing energy, while the plastic deformations occur quasi-isotropically.

If a steel plate, the thickness of which is relatively small with respect to its width, is subjected to tension or compression, flow lines (Lüders' lines) will appear at the yield stress which indicate the strips where the material is plastically deformed. Because at the yield stress the resistance of the material does not increase with further plastic deformation, so that such a plastic strip remains the weakest place, plastic deformation will initially be limited to this strip alone. This continues until its resistance increases, due to strain hardening, and another strip comes to its turn.

The writer proved that for a material where yielding and the mechanism of deformation are governed by the above-mentioned laws, the strips with the least resistance against local plastic deformation in such plates make angles of 55° with the direction of the tensile or compressive force or of 35° with the planes on which these forces act. These are indeed the actual directions of the flow lines in wide and thin steel plates. If such a plate is subjected to a plane state of stress $\sigma_1 \sigma_2$ (with $\sigma_2 < \sigma_1$), the dangerous planes in which these strips occur include angles with the plane on which σ_1 acts, which are given by

$$\tan \alpha = \sqrt{(\sigma_1 - 2\sigma_2)/(2\sigma_1 - \sigma_2)} \qquad (16)$$

These angles may be found more directly as follows. Since these plastic strips have a width of the same order of magnitude as the plate thickness, the plastic deformation in the direction of the thickness is not impeded by the adjacent material. Unimpeded yielding will only be possible if the plastic deformation in longitudinal direction of the flow line is not impeded. This will be the case if, in the state of stress to which the plate is subjected, the plastic strain in the direction of the flow lines is zero. This condition is fulfilled for the above angles [BIJLAARD, 1940-41].

It may be assumed that for a superimposed tangential compressive stress, the stress-strain diagram for the Earth's crust as a whole shows a maximum, at which point consequently strips of local plastic deformation will occur, for which the angles given above apply.

In case of compression such a strip or belt will tend to show a symmetrical thickening with respect to the adjacent parts of the crust. The isostatic equilibrium requires, however, that it should protrude more downward than upward. Hence it would be situated too high and would consequently represent an excess load on the crust. This load will bend the crust down. The tangential compressive force will now bend it down farther than the isostatic equilibrium requires, causing narrow strips of negative gravity anomalies. Since the crust is elastically supported by the substratum, this leads to adjacent waves of smaller amplitude where the crust bends upwards, causing relatively smaller positive gravity anomalies. In the sinking wave, containing the plastic belt, sedimentation will occur which, in connection with the compressive force, bends the crust farther down. Thus a geosyncline is created [BIJLAARD, 1935, 1936a, 1948].

Owing to increase of temperature, intrusion of magma, and other factors, the resistance of the crust decreases, so that finally the geosyncline is squeezed together, forming an island series. The dying out of the compressive force and partial melting of the root tend to reestablish isostatic equilibrium, in consequence of which the belt rises and forms a chain of mountains.

This conception is supported by gravitational and geological evidence in the East Indies and the Western Pacific. The island series bordering East Asia, for example, cross each other at angles of about 110° at the islands of Hokkaido, Kyushu, Formosa, and Guam. This points to compressive forces exerted by the Asiatic Continent on the ocean floor [BIJLAARD, 1936a].

The oblique direction of the geosynclines with respect to that of the compressive force may explain also the creation of volcanism. Owing to its bending the resistance perpendicular to the

geosyncline will decrease. Since the adjacent parts of the crust tend to move in the initial direction of the compressive force, this will create excess shearing stresses in the geosyncline and in the adjacent crust, causing excess tensile stresses in vertical planes situated approximately in the direction of compression. This may cause cracks allowing the magma to rise and to create volcanoes. These cracks and volcanoes will arise outside the deformed belt because the crust is here less plastically deformed and thinner [BIJLAARD, 1936a].

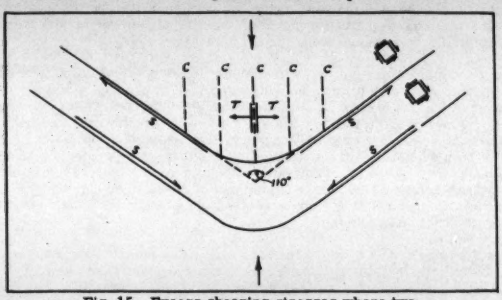


Fig. 15--Excess shearing stresses where two deformed belts cross

The excess shearing stresses are indicated in Figure 15 showing the case where two deformed belts cross. Here the excess shearing forces S exerted by the belts on the adjacent crust create excess tensile forces T in the crust at the concave side of the belt, causing cracks C and thus volcanoes at the inner side of the arc.

The writer's theory [BIJLAARD, 1936a] explains also the curved connection of intersecting belts or the arclike form, such as in the Ryukyu Islands. Furthermore, if the state of superimposed tangential stress is such that $\sigma_2 > \sigma_1/2$, Eq. (16) yields imaginary values. In that case pure shear planes occur in the planes of maximum shear stress, making angles of 45° with the plane of the crust, by which rift valleys may be created [BIJLAARD, 1948].

By his subsequently developed theory of the plastic buckling of plates the writer [BIJLAARD, 1938, 1949] could prove that the crust will not buckle before plastic deformation strips are formed. If the compressive stress reaches the point of the stress-strain diagram where $d\sigma/d\epsilon = 0$ (σ = stress, ϵ = strain), a column has a zero flexural rigidity. At the same point a plate, however, has still a very considerable flexural rigidity and hence a considerable rigidity against buckling. The writer's theory was confirmed by numerous buckling tests on aluminum plates by Kollbrunner and by the National Advisory Committee for Aeronautics [BIJLAARD, 1949].

Cornell University,
Ithaca, New York

DISCUSSION

Nadai asked what brings about the horizontal compression. Bijlaard replied that the cause was sought in convection currents below the crust.

Bullard mentioned that the sinking is a very slow process, which takes much more time than the buckling itself (the formation of the mountain range apparently represents only a few per cent in time duration of the whole story). The sinking appears when the temperature at the underside of the block has risen sufficiently; this temperature rise, due to low thermal conductivity of the sediments, may be of the order of 300° C.

REMARKS ON DEFORMATION OF THE EARTH'S CRUST

E. C. Bullard

There are two widely held views on the cause of the deformation of the Earth's crust. The first, which has been supported by Jeffreys, is that the crumpling observed in mountain ranges is due to the adaptation of the cold exterior to the contraction of the cooling interior. The other view supposes that the stresses which cause mountain building are the shear stresses associated with convection currents in the material immediately below the crust.

There has been much controversy as to whether Jeffreys' mechanism is adequate. Until recently the geological estimates of the shortening required to produce a major mountain range have been of the order of 300 km and far in excess of what thermal contraction can provide. These estimates are, however, contradicted by the estimate of shortening obtained from the volume of the roots of the mountains revealed by gravity survey. The geological estimates of the shortening are much reduced if it is supposed that the isolated blocks that were previously thought to be the remains of continuous nappes have slid downhill to their present positions. It is of fundamental importance to inquire whether a reasonable adjustment on these lines can bring the geological and gravimetric estimates of shortening into agreement and whether the gravimetric estimate is consistent with the contraction hypothesis.

The contraction hypothesis is much less attractive now than it was ten years ago, since most cosmologists now require an initially cool Earth that subsequently gets hotter. If this is so, there is no contraction and we are forced to seek some other cause for folding. The suggestion that has been most considered is that of convection currents. Vening Meinesz, Griggs, Hess, and others have given an attractive account of the genesis of island arcs and mountain ranges from this point of view. The argument would, however, be more convincing if there were strong evidence for a system of forces tending to produce convection and some independent reason for believing in their existence. The currents are usually supposed to be driven by the action of gravity upon a density difference between the matter beneath the oceans and the continents. This difference in density is supposed to be due to the material beneath the oceans being cooler than that beneath the continents, as a result of the lesser radioactivity of the oceanic rocks. An independent check on this rather tenuous argument is desirable and appears to be possible. The work of Pettersson and of the Scripps Institution of Oceanography has shown that it is possible to measure the rate of flow of heat through the floor of the ocean. On the hypothesis described above this should be markedly less than for the continents. At present we have only preliminary results. Their verification and extension is one of the most important problems of experimental geophysics.

National Physical Laboratory,
Teddington, England

DISCUSSION

Jean Goguel (Ecole des Mines, Paris, France)--Nous n'avons point de raison de mettre en doute que l'équilibre isostatique ne constitue la loi qui détermine, à chaque instant, la hauteur à laquelle s'établit chacun des compartiments de l'écorce. Mais la geologie nous fait connaître de nombreux déplacements verticaux qui ne résultent pas simplement du jeu de l'isostasie. Bucher a rappelé le soulevement des zones plissées postérieurement à la fin des mouvements tectoniques. Dans l'accumulation de très épaisses séries sédimentaires, la compensation isostasique n'explique qu'une partie du soulevement d'un massif soumis à une érosion profonde. Les plateaux du Colorado, soulevés de quelques 2000 mètres depuis le Crétacé, sans érosion sensible, fournissent un exemple particulièrement frappant d'un tel déplacement vertical spontané.

Au cours d'une phase d'activité tectonique, on peut faire appel, pour expliquer les déplacements verticaux, aux forces exercées par les courants de convection, mais il ne faut pas s'exagérer leur rôle. Un calcul détaillé serait nécessaire pour préciser dans quelle mesure les courants ascendants pourraient produire un soulèvement de la surface, sans que la surpression correspondante ne freine beaucoup leur mouvement (ou l'inverse pour des courants descendants). Je ne pense pas non plus que les compressions tectoniques horizontales puissent, en agissant sur une arche, concave ou convexe, produire une composante verticale susceptible de déterminer sur quelques dizaines de kilomètres un écart notable à la compensation isostatique: pour l'ensemble de l'écorce, les compressions horizontales (comptées à partir de la pression hydrostatique) sont faibles par rapport aux pressions verticales; d'autre part, pour des régions étendues, les arches sont très surbaissées.

D'ailleurs, la question essentielle qui se pose est d'expliquer les déplacements verticaux qui subsistent après la fin des mouvements tectoniques, ou se produisent indépendamment de ceux-ci, et qui traduisent donc un changement permanent dans la densité des parties profondes le l'écorce, tel que la production de racines relativement légères sous une région plissée. Pour les régions qui n'ont pas subi de déformation tectonique, le changement de densité des parties profondes doit être expliqué autrement; on peut songer à une recristallisation, ou inversement une fusion des cristaux, ou encore a une transformation polymorphique, toutes transformations qui impliquent une absorbtion ou un dégagement d'énergie sous forme de chaleur latente.

Aucune hypothèse sur la géophysique profonde ne sera satisfaisante si elle ne rend compte, en même temps que de l'évolution des orogènes, de ces changements dans la densité de l'écorce.

J. M. Burgers (Institute of Technology, Delft, Holland)--One should be careful in extrapolating from what has been observed in the compression of a metal sheet or block to phenomena in the Earth's crust. A sheet of metal is a nearly homogeneous arrangement of crystals, whereas the crust of the Earth is extremely inhomogeneous, even if we look only to the surface pattern and average over the whole depth.

THERMODYNAMIC THEORY OF PERI-CONTINENTAL LIMINARY ZONES

M. L. Glangeaud

Location of border mountain ranges--A synthesis made on a world scale reveals the existence of several types of orogenic systems.

On a shield, a deformation having a curvature of large radius may be accompanied by various phenomena resulting from vertical faulting. This type appears in regions which, at a given geological epoch, were situated far inland from the edge of the continental land mass.

The second type corresponds to what we have called liminary ranges, which nearly always border the continental land mass between the emerged areas and the ocean bed. It is this type which is predominant in all folded continental borders, whatever their nature. Such liminary ranges surround, for example, the Pacific Ocean. To this type also belonged the edges of the Alpine range (the African edge plus the Eurasian edge) before the Eocene age, but, in the Tertiary period, the final orogenic phase imposed an overthrusted structure on the original liminary structure.

All folded ranges pass at a given moment through the liminary stage. At this stage a moderate folding process is accompanied by a limited movement of the surface material between dislocated masses, some of which may have subsided, others of which may have been lifted. Such a structure exhibits a great instability in time and space. The crust, although highly deformed, still plays a controlling influence. It is on the edge of such ranges that roots and buckling appear, phenomena demonstrated by the notable works of Pekeris, Griggs, and Vening Meinesz.

Gutenberg has shown in a number of publications that the crust under the Pacific Ocean has seismic properties markedly different from those of the American and Asiatic continents. Accordingly, there is probably sima (ultra-basic material) under the Pacific and sial under the American continent. It is almost solely on the boundary between the continental sial and the material under the Pacific that the characteristic types of peri-Pacific liminary structure are found.

A quite simple thermodynamic explanation of the formation of these liminary ranges can be found.

Variations of the properties of the crust along a vertical line--The properties and the relation of the constituents forming sialic and simatic crusts do not change in a simple way with depth:

(a) Quartz and many minerals show sudden variations of properties at temperatures near their point of transformation. For example, the transformation from α- to β-quartz (at 573°) under normal pressure is accompanied by important variations of the coefficient of diffusion and of the elastic, thermal, and other properties.

(b) There exists between two minerals in contact an interfacial field. This field is rapidly modified and even in part inverted when pressures are created above the internal pressure of the crystals. At higher pressures there appear important changes in the coefficient of diffusion of the constituents exchanged between two neighboring minerals. On a geological time-scale, such phenomena may have a profound influence.

(c) The amount of radioactive matter does not show a regular variation with depth.

(d) The thermodynamic derivatives of the volatile constituents such as water vapor in its hypercritical state undergo great changes with slight variations of temperature above certain critical temperatures, for example water vapor between 300° and 500°.

It is difficult to calculate the effects of these different phenomena as a function of depth. We can, nevertheless, venture the likely hypothesis that the thermodynamic characteristics of the crustal material change in a complicated way with depth. Thus there exist certain levels where rapid variations of thermodynamic potential exist, and where, as a consequence of diffusion, plasticity and other characteristics important in crustal mechanics change rapidly. We shall call these levels thermodynamic-sensitive zones. For instance, one of these levels corresponds to the critical temperature of water vapor, another to the point of transformation from α- to β-quartz.

Horizontal variations of the crust's properties--It is logical to assume that, in any homogeneous continental crust, variations in the properties of the crust and the depths of thermodynamic-sensitive levels are the same along any two vertical lines. Such vertical variations will not introduce a horizontal gradient between two neighboring cylinders of the continental crust. The same must be the case for the crust under the ocean in so far as this crust is homogeneous. On the other hand, if the composition of the crust changes horizontally, the thermodynamic functions of the crustal material differ from one place to another. Gradients appear along any horizontal surface.

If at a given depth and place a particular property has a maximum value while in a neighboring mass at the same depth it has a minimum value, a maximum horizontal gradient exists for the property in question at the depth under consideration. Thus the co-existence at a distance of a hundred kilometers of two different materials results in a lack of thermodynamic equilibrium. For example, a disturbance in equilibrium may appear between sialic and simatic regions of the crust, since these have a different content of volatile and radioactive material.

In all probability it will be difficult to assemble all the quantitative and experimental data permitting the measurement of these complex phenomena. To calculate the resulting mechanical and chemical phenomena is an even thornier problem.

Lack of liminary equilibrium and orogenic forces--Simple reasoning shows the probable geological importance of these thermodynamic gradients. Even if these gradients between two different parts of the crust are too slight to provoke orogenic phenomena, they constitute, nevertheless, potential sources for local anomalies. Such anomalies are seen at work in the positions of folds and of volcanoes.

For example, let us examine Pekeris' theory of convection currents. His theory has received support from investigations of Vening Meinesz and his school. Nevertheless, certain problems are not yet solved. For instance, this theory does not take into consideration the important atomic or structural modifications which may take place during the upward movement of matter starting from a depth of 2900 km and ending only 100 km below the surface. Between such different depths, this matter will cross points of transformation constituting veritable thermodynamic barriers. Further, such vast convection currents, involving the whole mantle of the Earth, do not explain the observed positions of liminary orogenic zones bordering a continental land mass. Nevertheless, the findings of Vening Meinesz support this theory.

If, on the other hand, we admit local thermodynamic anomalies in the regions where sial adjoins sima, we have a further means for explaining by local convection currents such geographical configurations. These currents can be produced by thermal gradients similar to those in a glassmaker's furnace. Experiments of Velikoskys and Avsec show that the form and dimensions of convection currents are influenced by conditions which have existed before the currents started. These currents depend to a large extent on conditions at their boundaries.

If orogenic theories are based on tangential forces of various origin (such as continental drift and thermal cooling) instead of on convection currents, the existence of pre-established crustal anomalies still plays an important part in the localization of phenomena produced by these forces, as I have shown for several liminary ranges (such as Jura, African Atlas, and Californian range). All these ranges have an inheritance imposed on them by their previous history. Even if the sialic-simatic liminary gradients do not suffice to initiate orogenic phenomena, they still introduce important anomalies which will localize the later action of other orogenic forces.

The explanation of these facts is relatively simple when we establish the evolution of the ranges bordering the Pacific, which, according to seismological data of Gutenberg, appear to be situated on the boundary of the continental sial and the Pacific ultra-sima. We have, moreover, worked out the consequences for the formation of the Mid-Atlantic Ridge. Rothé has based on Gutenberg's seismic data the hypothesis that the Atlantic bottom is not formed of a single kind of material. He believes that the eastern portion of the Atlantic has a granitic crust and that the western portion is formed of basalt. The presence of basalt in the western sector is indicated by the work of Ewing and his collaborators. In view of these facts, we may wonder if the Mid-Atlantic Ridge is not a liminary range, formed in the area where the basaltic crust of the western Atlantic passes into the sialic crust of the eastern Atlantic.

Other facts of a paleo-geographical, geophysical, and tectonic nature could be mentioned in favor of the thermodynamical theory of liminary ranges. This theory seeks logically to account for tectonic and paleo-geographical facts without introducing orogenic mechanisms, which can be verified only with great difficulty.

Addendum--Calculations based on the heat current through the Earth's surface indicate that an amount of energy of 1.4×10^{28} cal has been radiating from the Earth into space for 150,000,000 years. The orogenic processes involve only 1.6×10^{25} cal. Hence there is an amount of energy available much larger than that which is needed for the explanation of orogenetic phenomena.

Faculty of Sciences,
Besancon, France

DEFORMATION OF THE EARTH'S CRUST IN GEOSYNCLINES

F. A. Vening Meinesz

The belts of negative anomalies in Indonesia, near Japan, in the West Indies, and elsewhere, where tectonic crustal deformation has recently taken place, have led to the assumption that in these belts the crust has buckled downwards under the effect of strong horizontal compression. Two facts seem to point to this phenomenon taking place as an elastic deformation, not as a plastic one. In the first place, it seems likely that plastic deformation by horizontal compression would lead to a bulging out of the crust to both sides, that is, at the surface and at the lower boundary of the crust in such a way that isostasy would remain valid, and this is obviously not the case.

In the second place, the idio-geosynclines on the inside of the tectonic belt in Sumatra and Java can easily be explained as a second wave of the crust if this crust is reacting elastically to the compression and the compression has exceeded the buckling limit of the crust.

There are, however, three serious difficulties in assuming an elastic deformation, which made the writer abandon this standpoint; he succeeded in removing the above objections to the hypothesis of plastic reaction of the crust. Bijlaard adopted this in 1935.

The first difficulty of the elasticity hypothesis is the large stress needed for crustal buckling; it amounts to 40,000-50,000 kg/cm^2 and the strength of the crustal matter can hardly be more than 3000 kg/cm^2. One way out is to assume the crust to consist of layers gliding over each other without appreciable friction, but this seems hardly admissible; more than 15 layers would have to be assumed. Another way out would be the hypothesis of Griggs that the downward buckle would be brought about by a downward convection current below it, but here we meet also with great difficulties. In particular, such local currents could hardly be reconciled with the regularity of the downbuckling arc over great distances in Indonesia as well as in the West Indies.

In the second place, elastic downbuckling of the crust seems difficult to assume in case we admit a small strength in the subcrustal layer. There are many arguments in favor of a strength of the order of 10 kg/cm^2 being present there.

In the third place, Bijlaard has shown that elastic downbuckling of the crust ought to originate in a more or less straight belt at right angles to the compression and this does not check with the curved pattern the tectonic arcs everywhere have adopted.

When abandoning the idea of elastic deformation of the crust in these belts we have, in the first place, to show that plastic deformation can lead to crustal downbulging. We find this to be possible because when in the beginning a two-sided bulge develops which is in isostatic equilibrium,

the bulge at the lower boundary of the crust is about 4.5 times as great as the surface bulge and this leads to an asymmetry in the compressive stress in the crust needed for keeping the resultant of the stresses in its place; the compression of the upper layer of the crust must thus become stronger than that of the lower layer and this must lead to a downward bend. It can be shown that after some time this downward bending movement gets the upper hand with regard to the rise of the surface caused by the outward bulging and this leads to an accelerated downward buckling of the crust.

It can likewise be shown that under certain circumstances this crustal deformation may lead to the development of a neighboring wave of the crust and this takes away the second objection against the hypothesis of plastic deformation of the crust in the tectonic belts. The second wave need not lead to a crustal downbulge and will, in fact, usually not do so.

We thus arrive at the hypothesis that the crust in the geosynclines gives way by plastic deformation after the compressive stress has exceeded the strength-limit. This hypothesis makes it possible to come to an explanation of the curved pattern of the tectonic belt. This is founded on the fact that plastic deformation in the crust (as in all plates of which the thickness is small with regard to its other dimensions) ought to occur in belts making an angle α with the direction at right angles to the compression, α being given by Bijlaard's formula

$$\cos 2\alpha = (\sigma_1 - \sigma_2)/3\,(\sigma_1 + \sigma_2). \quad (17)$$

where σ_1 is the main compressive stress and σ_2 a possible stress in a horizontal direction at right angles to σ_1. When σ_2 is zero, as it probably will be in most cases of tectonic deformation, we find

$$\alpha = 35°$$

Now it is interesting to see that in Indonesia great parts of the two tectonic arcs approximately make this angle with the direction in which we may assume the compression to take place, while the other parts make a small angle with this last direction and the relative movement of the crustal blocks on both sides of these last parts is mainly shearing. It thus seems possible to account for most of the intricate pattern of the Indonesian arcs and this seems a strong point in favor of the hypothesis of plastic deformation of the crust in these belts.

Royal Netherlands Meteorological Institute,
De Bilt, Holland

PART III - GRAVITY ANOMALIES AND POSTGLACIAL UPLIFT

ON THE POSTGLACIAL UPLIFT OF LAND IN FENNOSCANDIA

W. Heiskanen

The uplift of land in Fennoscandia has been studied quite extensively. Using old shorelines, hundreds of meters above the present sea level, Finnish, Norwegian, and Swedish geologists have been able to measure the amount of uplift. We arrive at still more accurate results by comparing two precise levelings in Finland, the former carried out in 1892-1908, the second in 1935-1950 along the same railways and highways. According to the results [KÄÄRIÄINEN, 1949], the uplift in Finland is between 34 and 92 cm/100 years. The maximum is in the Gulf of Bothnia at latitude 64°. According to geologists, the land has risen during the last phase of the glacial period by a maximum of about 250 m, and afterwards by about the same amount.

Since the negative gravity anomalies in Finland become as large as -50 mgal as the center of the uplift area is approached, there seems to be a relationship between the uplift and the gravity anomalies, as Daly pointed out in 1941. This is easy to understand. Before the glacial period this area was in isostatic equilibrium. During the glacial period the Earth's crust sank about 700 or 800 m under the load of the ice cap about 2000 m thick until isostatic equilibrium prevailed. During this period the layers under the ice cap moved in a horizontal direction towards the unloaded areas and forced the land to rise a little on the periphery. After the melting of the ice, the land began to rise in the central region and to sink on a smaller scale near the periphery. The uplift in the central area and the subsidence near the periphery still continues, as the measurements in the area of uplift and the drowned forests near the periphery show.

At the present time the flow of the subcrustal material should be directed towards the center. Since not all the mass flowing outward during the glacial period has had time enough to move back, there is too little mass under the uplift area and, therefore, the gravity anomalies here are negative. If the subcrustal masses had only moved downward during the glacial period and upward afterwards, the amount of the mass under the glacial areas would not have changed, so that there could hardly exist any systematic negative gravity anomalies. The existence of the negative gravity field in the postglacial uplift area is, therefore, evidence of the horizontal movements of the subcrustal masses. However, it should be understood that effects of local density differences make the phenomenon more complicated, and that the gravity anomalies are not due only to the uplift of land but also to local causes.

Ohio State University,
Columbus, Ohio

DISCUSSION

David Griggs (University of California, Los Angeles, California)--The quantitative measurements of the uplift of Fennoscandia have provided the only test to date of the "viscosity" of the outer shells of the Earth. HASKELL [1935] obtained a solution for the case of a semi-infinite Newtonian fluid subject to a circular plate load. Using the values for the rate of uplift from Fennoscandia, this yields a viscosity of 10^{22} poises. Vening Meinesz and Niskanen extended this solution to layered fluids, and showed the effects of different viscosities in several hypothetical layers. It would be most desirable if solutions could be found for the case of non-Newtonian viscosity--for example, a stress dependent "viscosity" of the type described by Burgers.

E. C. Bullard (National Physical Laboratory, Teddington, England)--There are regions with considerable positive or negative gravity anomalies where there is no motion, thus contrasting with Fennoscandia.

B. Gutenberg (Seismological Laboratory, California Institute of Technology, Pasadena, California)--Earthquakes are frequent in many of these areas, thus indicating active tectonic processes. On the other hand, there are few and small shocks only in the areas of postglacial uplift (Fennoscandia and North America), indicating passive return towards equilibrium.

ON THE LARGE POSITIVE AND NEGATIVE GRAVITY ANOMALY FIELDS

W. Heiskanen

The gravity field maps of TANNI [1948], which give the mean gravity anomalies of squares one by one and five by five degrees, show clearly that there are extended regions (diameter about 2000 to 3000 km) where all gravity anomalies are positive, and other large areas with negative gravity anomalies. For instance, in Europe from Sweden to the Alps, and from Poland to the English Channel, as well as in the eastern part of the Atlantic and in the western basin of the Mediterranean the isostatic anomalies are up to +30 mgal positive, and in Central Asia and India to -30 mgal negative. What might be the cause of these anomalies?

When more gravity data are available, perhaps these areas will become smaller. Perhaps there will be some bridges of negative gravity anomalies across and some isolated islands of negative gravity anomalies in the positive gravity field and vice versa. However, the fact remains that large regional positive and negative gravity anomaly areas exist. Since the distance between the largest positive and negative areas is about 90°, the gravity field seems to agree with the longitude term of the gravity formulas and consequently with the triaxial earth ellipsoid. The fact that the regions of positive and negative anomalies in different latitudes are in general not situated at the same longitudes agrees less well with the triaxiality. For instance, in the southeastern United States the gravity anomalies are regionally negative, but a little to the south in the Gulf of Mexico, at the same longitude, they are regionally positive.

Whether the Earth is a triaxial ellipsoid or not, there must exist, in addition to the usual compensating masses, some regional disturbing layers, which bring about the large gravity anomalies. The regional gravity anomaly field of +30 mgal would indicate an additional mass corresponding to a 300 m thick layer of density 2.4, and the field of -30 mgal a defect of an equal mass. Even larger disturbing masses may exist in tectonically young regions, as in the western basin of the Mediterranean, under the belts of negative gravity anomalies and in all such regions where

horizontal movements of masses (perhaps in connection with convection currents) are now going on. It is much more difficult to explain that such anomalies exist also in "quiet" regions as in Central Europe north of the Alps and in India. In the light of the Fennoscandian uplift these disturbing masses, though relatively small, are so large that neither the Earth's crust nor the subcrustal layers can support them unless tectonic forces are in action. Therefore, we have to suppose that these disturbing masses are isostatically compensated.

Most of the topography will be compensated in the roots and "anti-roots" about 20-50 km below the surface; if we assume that this "secondary" compensation occurs evenly from the layers at depths of 50 km down to depths of about 500-700 km, the density difference of these masses need not be too large, only of the order of 0.001. If this assumption is correct at least in a general way, the masses of the upper layers of the Earth are first compensated in the region of the deep-focus earthquakes, about 500-700 km below the surface.

Ohio State University,
Columbus, Ohio

DISCUSSION

The discussion turned once more to the forces in the crust. Bullard asked whether one can assume that the material has a finite strength. Benioff pointed out that from the intervals between earthquakes it follows that there is sometimes an accumulation of elastic stress without much release through flow over a period of from 6-15 years. Gutenberg drew attention to the fact that the greatest deep-focus earthquakes have roughly one-tenth of the energy of the greatest near-surface earthquakes; there is, however, very little change between 300 and 600 km. A discussion followed on the magnitudes of the stresses and the volumes involved. The duration of deep shocks is at most 10 sec; the velocity of propagation 10 km/sec; hence a sphere with 100-km radius would give the order of magnitude of the maximum volume involved. The shear stress which must be held by the material can be estimated to be of the order of 10-100 kg/cm^2. From these data an estimate of the energy can be derived.

Prager mentioned the solution for plastic stresses in a material under the action of a uniform pressure over a long narrow zone and asked whether there is any geological evidence for the existence of such a case.

Bullard returned to the question as to how the great masses which Heiskanen mentioned are supported. How are the great plateaus of the world, such as the highlands of Africa, raised and supported? They appear to be raised without great horizontal stresses or much bending, and to be in isostatic equilibrium. It is difficult to suppose that this is a result of convection currents. What is required is a vertical force roughly uniform over an area a few thousand kilometers across. This force is clearly different from that needed in mountain building. It is attractive to suppose that some phase change of material at great depths is involved. Bijlaard stated that in the case of the Himalaya mountains the central pressure acting vertically on the crust is of the order of 1500 km/cm^2; lateral forces of a magnitude 3500 kg/cm^2 would be needed to press these mountains up. On a further question brought forward by Vening Meinesz and others concerning the calculation of the viscosity of the substratum from the postglacial uplift of Scandinavia, the following was offered.

P. P. Bijlaard (Cornell University, Ithaca, New York)--In connection with the objection that the rigidity of the crust had been neglected in these calculations, it was shown that the rigidity of the crust actually is unimportant [BIJLAARD, 1936b]. The crust is not able to support significant loads if bent in waves of large length. In the postglacial uplift of Scandinavia the crust may be assumed to bend cylindrically as a plate of about 1400 km span that is clamped at the edges. To give the crust a maximum upward deflection w = 500 m, a negative parabolically distributed load of maximum intensity p would be needed, which follows from the equation

$$w = (13/15)\,(1/384)\,(pL^4/N). \qquad (18)$$

where

$N = (Et^3)/12\,(1 - \nu^2)$
L = the span of the plate = 1400 km = 14×10^7 cm
t = the thickness of the rigid crust = 30 km = 3×10^6 cm
E = the elastic modulus of the crust = 1,000,000 kg/cm^2
ν = Poisson's ratio = 0.2

This yields p = 0.125 kg/cm^2.

Since (with a density 3.3 of the substratum) an uplift of 500 m requires a negative load by melting of the ice cap of 500×0.33 kg/cm^2 = 165 kg/cm^2, it follows that the rigidity of the crust decreases the uplift by only 0.125/165 = 0.00075 or 0.075 pct.

The curvature of the crust which was neglected in this calculation by assuming the crust as a plate causes a decrease of the same negligible order of magnitude.

David Griggs (University of California, Los Angeles, California)--If we consider a fault, and assume that tangential stresses of a magnitude 10 kg/cm^2 are acting in planes 500 km apart, and if, further, we assume a viscosity of 3×10^{21} poises, one would obtain a relative displacement of 500 km in 10^7 years. The presumed motion of the continents was mentioned in this connection; a velocity of 5 m in 100 years was tentatively mentioned, which would give about 50 km in a million years.

Glangeaud mentioned effects of shear along the Jura Mountains. Folding is perpendicular to the direction of shear. There should be two different causes. Bucher observed that these are mainly surface effects.

Jean Goguel (Ecole des Mines, Paris, France)--Les anomalies isostatiques sont susceptibles d'interprétations assez différentes: certaines correspondent réellement à un défaut d'équilibre, qui se traduit directement par un déplacement vertical, comme en Scandinavie et dans les autres zônes abandonnées par les glaciers quaternaires.

D'autres tiennent à des irrégularités de la structure de l'écorce, dans laquelle la répartition des densités ne ressemble que de fort loin à celle qui a été supposée pour le calcul des corrections isostatiques; de ce nombre sont les anomalies locales, auxquelles s'intéressent les prospecteurs, et qui correspondent à de petites structures, non individuellement compensées. Mais il y a également des irrégularités de densité plus profondes, voire des différences notables dans la densité de l'écorce, sur des étendues inférieures au rayon de régionalité, qui ne donnent pas lieu à une compensation individuelle. Cependant, l'étude gravimétrique du bassin parisien m'amène à penser qui certaines déformations proviennent de ce que la compensation, d'abord très régionale, tend progressivement à devenir de plus en plus locale.

Il y a, enfin, des anomalies très étendues, indiquant des écarts notables du géoide par rapport à l'ellipsoide. Le fait que l'on ne constate pas de déplacements verticaux montre qu'elles ne correspondent pas à un déséquilibre de l'écorce sur le magma profond: l'exemple de la Scandinavie, région dépourvue de toute deformation tectonique récente, nous montre en effet à quel point le déplacement vertical est sensible à tout déséquilibre réel.

L'origine de ces anomalies doit donc être cherchée plus bas, peut être jusque dans le noyau, dont le brassage par des courants doit se traduire par des ondulations de la surface, et sans doute aussi au niveau des courants de convection éventuels; ceux-ci doivent intervenir, tant par les différences de densité qu'ils impliquent, que par le déséquilibre dynamique dont ils témoignent.

Je pense que, lorsque la forme du géoide aura pu être déterminée par les Géodésiens, elle nous fournira un renseignement très important sur la localisation des courants de convection.

PART IV - CONVECTION CURRENTS

SUMMARY OF CONVECTION-CURRENT HYPOTHESES OF MOUNTAIN BUILDING

David Griggs

Modern convection-current hypotheses of mountain building date from the discovery of the strong negative gravity anomaly paralleling the East Indies Island arc by VENING MEINESZ [1934] and his suggestion of a convective origin of these features. PEKERIS [1935] carried out a more complete mathematical analysis of convection in the Earth's solid mantle, and the probable stresses on the Earth's crust and velocities of flow, which corroborated and extended Vening Meinesz' analysis. GRIGGS [1939b] suggested that convection in the mantle would take the form of intermittent over-turns of thermally unstable regions, and attempted to correlate the phases of such an overturn with the mountain building cycle. BROOKS [1941] extended Pekeris' analysis to include convective heat transport, analyzed the fundamental modes of motion, investigated the time required for convective overturn, and estimated the effect of plastic rather than true viscous

flow. His analysis of the modes of motion showed how cooling under the Pacific Basin would give rise to two concentric convection cells, the outer one having downflow under the edges of the continents, accounting for the Tertiary Circum-Pacific Mountain Belt and predicting high heat flow through the Pacific floor. He further states that during the decelerating phase of the convective overturn, convective motion tends to dissipate itself into smaller cells, perhaps accounting for the island arcs around the Pacific Basin.

A principal uncertainty in convection hypotheses is the unknown composition of the Earth's mantle. In order that thermal convection be important in its mechanical effect on the Earth's crust, the outer several hundred kilometers of the Earth's mantle must be free from stable density stratification or density gradients except for reversible, pressure-induced changes such as hydrostatic compression or polymorphic transitions. An inherent density discontinuity (for example, compositional stratification) of one per cent will serve as an important bar to convection. To date, seismological observations have not established the existence of such a density discontinuity short of 2900-km depth. Francis Birch, however, will present an interpretation of seismic evidence which favors inhomogeneity of the outer mantle, and thus poses a problem to advocates of convection hypotheses.

Many recent developments are consistent with convection hypotheses. The treatment by BENIOFF [1949; present paper] of earthquake sequences leaves little doubt that intermediate and deep-focus earthquakes reflect profound flow at depths to several hundred kilometers with important horizontal components. The regions of such flow coincide with regions of most intense negative gravity anomalies. Ewing and co-workers have extended the survey of gravity anomaly strips to half a dozen new localities. To date it can be said that at every region yet explored, where deep earthquakes indicate present subcrustal flow, strong negative gravity anomalies have been found, as predicted by convection hypotheses.

Thermal gradient studies by the Scripps Institution of Oceanography in the Pacific during 1950 provide a tentative indication that the subcrustal heat flow there is some three to four times as great as under the continents. It follows that at a constant pressure level, some 50 km below mean sea level, the substratum is some 200° C hotter under the oceans than under the continents This is consistent with a recent overturn in the mantle under the Pacific.

Mathematical treatments of convection, while presenting strong arguments for the existence of convection in a homogeneous mantle, are still far from complete. In particular, it is desirable that heat transport be included in the equations, that the growth of convection from a reasonable quiescent state be investigated, and that plastic flow rather than true liquid viscosity be studied. BROOKS [1941] has made an attack on the problem in a very brief paper. It is hoped that he and others will carry forward this work.

University of California,
Los Angeles, California

COMMENT ON MOUNTAIN BUILDING

H. H. Hess

If one assumes that island arcs represent an early stage in the development of alpine-type mountains, then several currently accepted hypotheses are open to question.

Geosynclines--There is a concept put forward by James Hall a century ago that geosynclines, long narrow troughs filled by a great thickness of sediments, represent the zones of weakness which will give way to form mountain structures when the Earth's crust comes under compression. It was a very reasonable hypothesis and it is accepted almost unanimously by geologists today. Nevertheless, when confronted by the facts of island arcs, it does not seem to be true. In the East and West Indies there was no geosyncline with a great thickness of pre-Tertiary sediments under the belt which has been deformed. In the Swiss Alps, where the deformation was initiated in the late Jurassic, there was no great thickness of pre-Cretaceous sediments

Some geosynclines develop, however, as a result of island arc deformation. The geosyncline of eastern Venezuela and the one in eastern Sumatra are of this type. As the forces which initiate island-arc deformation subside, the belt of strong deformation may rise, thus providing an abundant source of clastic sediments to fill the long troughs which parallel it. Later renewed compression may fold and thrust fault the sedimentary sequence of the geosyncline. Even the classic Appalachian

geosyncline, from which Hall derived his idea, is of this character. It was related to an Ordovician island arc, the deeply eroded roots of which now appear as the metamorphic rocks of the Piedmont Province and its northward extension.

Other types of great geosynclines exist, such as that of the northern coast of the Gulf of Mexico today. There is no good reason to suppose, however, that such a geosyncline will localize future mountain building. The great thickness of sedimentary rocks of Beltian age in the present Rocky Mountain province persisted undeformed for more than one-third of a billion years and seems only by chance to have been transsected by the Laramide deformation. Strong deformation to the west of it had taken place earlier in the Mesozoic.

Roots--In the formation of mountains the concept is often advanced that the compression of the crust thickens it in such a manner that the mountains bulge upward and a larger supporting root bulges downward. This describes what we see in present mountains but is wide of the mark in explaining how mountains came to be. Here again the evidence from island arcs is clear. The root forms first and may, if the forces which produced it persist, remain a root without a mountain above it for 50 million years or more.

The above point is of critical importance in the explanation of the process by which the crust buckled or bulged downward to produce the observed gravity anomalies of island arcs. If the downbulge were a result primarily of forces exerted within the crust itself such as by thermal contraction, one cannot account for persistence of the root for as long a period of time as necessitated by the geologic history of both the East and West Indies. In both instances the root must have developed toward the close of Cretaceous time, more than 70 million years ago. In a small fraction of this time the root would heat up (both as a result of its own relatively high radioactivity and by rise of the geoisotherms to horizontality by conduction) to a point where its materials will partially melt. It will then have virtually no strength. The crust pushing into it from the sides cannot hold it down. There would be little to prevent it from flowing laterally and spreading out as a sheet. On the other hand, if the forces that produced the root were exerted by viscous drag on the lower surface of the crust by slowly moving currents in the substratum as exemplified by Griggs' experiments, then there is no longer any difficulty in holding the root in place or in explaining roots without mountains above them. The downward drag of the current is balanced by the upward force of the buoyancy of the semi-liquid V-shaped mass at the apex of the descending current. If the current slows, the mass will rise proportionally, or if it increases in velocity, the mass will go deeper. This picture is not at all inconsistent with what is known of the instability of islands over the negative anomaly strip such as Barbados and Timor.

A multi-layered crust--In the argument as to whether the root in island arcs developed in a partly elastic manner such as in Kuenen's experiments (a downbuckle) or in a wholly plastic manner (a downbulge), I do not wish to take sides. Either proposition seems equally feasible at present. One point with regard to the downbuckling hypothesis has been overlooked. Vening Meinesz found, as had Smoluchowski before him, that the crust, if composed of a single layer, would most certainly shear before it buckled. Smoluchowski showed that if the crust were made up of several layers with low friction between the layers, buckling would be possible. Vening Meinesz postulated a six-layered crust and was able to show that buckling would occur using a reasonable figure for the strength of crustal materials. The assumption of low friction might be difficult to defend. Buddington has pointed out that it is highly probable that the crust as a whole is layered in the same manner as the Bushveld, Stillwater, and Skaergaard intrusions. This layering consists essentially of dimensional orientation of the constituent crystals of the rock such that their longer axes tended to lie in the horizontal plane. Friction between such layers would be relatively high but there would be at least millions of these layers in the crust. A recent investigation of an achondritic meteorite by Henderson and the writer showed that such dimensional orientation was present which, if one makes the usual assumption that meteorites are fragments of a disrupted planet, lends weight to Buddington's speculation that layering by crystal settling would be present in the crust. This multi-layering of the crust greatly improves the possibility of elastic buckling but the high friction between layers probably destroys the validity of any deductions which might be drawn from Vening Meinesz' equation as to the thickness of the crust involved or the wavelength of the induced folds.

A further speculative extrapolation may be made from the above. The island arc-alpine type of deformation is always initiated on the sea floor, but where the belt of deformation cuts deeply into a continent an entirely different type of mountain system results--the Rocky Mountain type. The former is characterized by the formation of the downbuckle or downbulge. In the latter, deformation takes place over a much wider belt, is characterized by fracture of the crust, and the typical igneous sequence of the island arcs is not present. The difference in behavior might well be

explained if the oceanic crust were horizontally layered and the continental crust had predominantly vertical foliation as a result of past strong deformation. The former is capable of buckling, but the latter would shear before it buckled. The differences in character of the igneous activity could also be explained by this hypothesis but this will not be attempted here.

Convection in the mantle--At present it is not possible to prove that convection currents exist in the mantle nor is it possible to show that they cannot exist. The difficulty of explaining persistence of the root in island arcs without appealing to such currents leads the writer to be strongly disposed to favor them. Recently Elsasser and Bullard independently arrived at theories of the Earth's magnetic field based on convection in the core. To have convection in the core necessitates convection in the mantle; otherwise, there would be no effective way of removing heat from the core-mantle interface and convection in the core would stop. Birch's objection to convection on the basis of a difference in character of the materials above and below a level near 900 km is not a serious obstacle. If this barrier is a pressure-induced phase change, a convection current could pass through it, the reaction taking place in opposite directions on the upward and downward limbs of the cell. If it were some other type of barrier, tandem convection cells might be set up one above the other as postulated above for the core-mantle interface. A somewhat different system of tandem cells is suggested by the writer to account for the pattern of deformation on the Earth's surface and a correlation with deep-focus earthquake data (see Fig. 16). Note shear directions at A and B are opposite to those at C to be consistent with Koning's results. The "mega cell" is a convection cell extending from 500 km to base of mantle. Outflow from under warmer continent and direction of flow of mega cell have to be such that both are favorable to the direction of motion of the "roller cell"; thus not all coasts of all continents need have associated island arcs. Gap in deep foci near 475 km is at level between roller and mega cell.

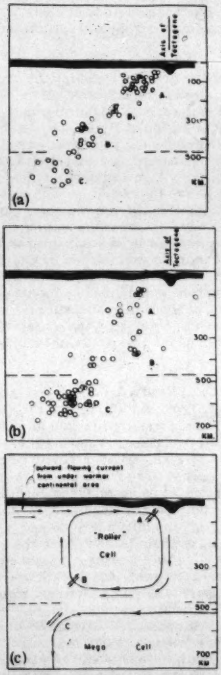


Fig. 16--(a) Composite profile of Guam to Honshu showing spacial relationships between deep-focus earthquakes and axis of tectogene or trench; (b) composite profile of Tonga-Kermadec Islands; (c) hypothetical convection cell system in relation to deep-focus earthquakes

Deep-focus earthquakes--The deep foci of earthquakes lie on the concave side of the island arcs in a zone sloping downward to a maximum of 700 km in depth as indicated by an immense amount of data compiled by Gutenberg and Richter. Is it possible that this 700-km maximun, the same level as Birch's ± 900-km discontinuity? The usual interpretation of the deep foci is that they lie along a ± 45° shear extending from the base of the tectogene inward and downward. The shear direction is always shown as upward on the upper side of the 45° plane. Such a direction of movement would fit the geologic picture as known in island arcs. The writer is very skeptical of this convenient 45° shear plane. The distribution of foci, when plotted, shows considerable deviation from such a plane beyond their stated error in location and shows certain regularities in distribution which require explanation (see Fig. 16). The writer would explain their distribution as related to a small convection cell.

Koning studied the first recorded motion at a large number of stations for one 700-km shock. He found the direction of shear movement to be the reverse of that commonly postulated. It would be downward on the upper side of a postulated 45° shear. It would be very desirable to investigate the shear direction for a number of deep-focus earthquakes of different depths.

The writer has noted a gap in the distribution of deep foci near 475 km. This is about the same depth as Bullen's last determination of the so-called 20° discontinuity (Gutenberg interprets the same data as a consequence of the "low velocity layer" at a depth of about 80 km and does not find a discontinuity at a depth between 400 and 500 km).

Finally, Benioff has recently made a most unexpected discovery that the elastic rebound strain increments of intermediate and deep-focus earthquakes of a given region indicate energy accumulation at a constant rate over long periods of time.

Conclusion--To convert the opinions and observations stated thus far into a unified theory of mountain building would require more data on several critical points. Among the most important are (a) a knowledge of the shear directions of deep-focus earthquakes at various depths; (b) data on the thermal gradient under the oceans; (c) an explanation of the high velocities of seismic waves on the ocean floor (24,000 ft/sec = peridotite?; Ewing and others in the Atlantic and recent results of the Navy-Scripps expedition in the Pacific); (d) further refinement of such data as presented by Birch by which he postulated a change in properties of the mantle at ±900 km. Finally, any general theory developed must be consistent with the broad pattern of deformation observable on the face of the Earth (the major tenet of Bucher's book).

Investigation of some of the problems outlined in this report are being carried out at Princeton University under a contract with the Office of Naval Research (N6 ONR 27008).

Princeton University,
Princeton, New Jersey

DISCUSSION

Discussion started from a remark by Hess that many regions of negative gravity anomalies are characterized by relative abundance of peridotite. This peridotite must have been formed during the early phase of the tectonic process, when a bulging down of the central part of the disturbed zone occurred and when sialic material came in connection with the deepest simatic material there. Metamorphic rocks frequently occur along the axis of negative anomalies. Hess asked how a situation producing a large negative gravity anomaly could be maintained without convection currents. Bucher drew attention to the formation of basins, which may be almost circular (as the Banda Sea); in such a case one cannot assume lateral compression. Can a phase transformation give an explanation? Remarks by Vening Meinesz are summarized in the next paper.

CONVECTION CURRENTS IN THE MANTLE

F. A. Vening Meinesz

The question whether convection currents in the mantle are possible has not yet been definitely answered; the fairly quick increase in density between about 200- to 1000-km depth as mentioned by Birch does not appear to favor it, but it does not seem finally to settle the point.

I want now to attack the problem from the other side and to give a short summary of the phenomena which could be explained by it and which appear difficult to account for along other lines.

In the first place, we have the following phenomena which could be explained by accepting convection currents of some 400-700 km in diameter in a horizontal as well as in a vertical sense. We could thus account for the sinking of deep basins in tectonically active areas as, for example, the Banda Sea inside the Banda arc, the Celebes Sea inside other tectonic arcs, both in the eastern part of Indonesia, and many other deep basins. The geologists (for Indonesia, for example, Umbgrove) have shown these areas to have been above sea level until a relatively recent period, that is, only a few million years ago. They are probably related to the folding and overthrusting in the surrounding arcs but the sinking follows these phenomena with a time lag of from 10 to 20 million years.

We could explain this by realizing that the concentration of sialic matter through folding in the tectonic arcs produces heating because of its greater content of radioactive constituents which brings about instability in the subcrustal layer, leading possibly to convection. This could explain the sinking as a result of shrinking through cooling of the column sinking below the basin inside the arc. It could also explain the sinking of the mean level in the whole area because of the cooling such convection must bring about in the layer below the convection. Lastly, these currents may account for the deep and intermediate earthquake foci, caused by the shear stresses attending these currents; the direction of shear in these foci agrees with that found for all three foci investigated (Koning, Ritsema). This direction does not agree with the idea of the crust under the ocean

being pushed under the continental crust along an inclined plane, as it has so often been surmised.

The facts given by Birch are shedding new light on these matters. It appears to me that if we assume that the transition layer, indicated by him between 200- and 1000-km depth, has the same chemical constitution, for example, olivine, but in different phases (the deeper and denser phase possibly being the cubic phase?), convection would still be possible, although we should have to take into account the energy needed for or provided by the phase change. Assuming that the change into the denser state would be favored by increase of pressure but counteracted by increase of temperature, we might imagine that because of the lower temperature in the current sinking below the basin, the change into the denser state would be intensified under a release of energy, while the higher temperature in the rising current under the tectonic belt would only bring about a slower decrease of the denser state because of the energy required for that transition. Thus the sinking of a basin combined with only a small rise in the tectonic belt might perhaps be even better explained than by convection only. This phenomenon might also make the basin persist longer than pure convection could account for. This seems also to be an asset.

A second group of phenomena could be explained by assuming much greater systems of convection; in many cases we should probably have to suppose them to go down through the entire thickness of the mantle. As GRIGGS [1939b] has already put forward, we thus could account for the pseudo-periodicity of the periods of great tectonic activity while the drag exerted by these currents on the crust could provide the great system of forces required for its deformation. Each convection current would only make a half turn, bringing layers of lower temperature (caused by the cooling of the Earth's surface) down and deeper layers of higher temperature up, and thus reestablishing stability. In the same way as was mentioned for the smaller type of current, the difference of temperature between the mounting and descending currents would bring about rising over the first and sinking over the second. We thus should be able to account for the regression on the continents during the first part of the active period. After the reestablishment of stability a long period of rest (characterized by transgression) would have to follow during which the cooling gradient would again develop with a difference of cooling below the oceans and below the continents, these last areas acting as thermal blankets. This differential cooling and the resulting horizontal temperature gradient would be effective in starting the next current system, bringing about a rising current under the continents and a sinking one under the oceans.

It is rather probable that in this whole phenomenon we have to distinguish between currents of two sizes, a smaller one responsible for the different periods of tectonic activity and a larger one taking place over the entire depth of the mantle which, at greater intervals than the first, would bring about the periods of especially strong tectonic activity (occurring at intervals of some 150-250 million years). We could imagine that the smaller type would bring about temperature disturbances at great depth in the Earth which would be operative in creating the circumstances needed for the larger ones. In the same way perhaps the smallest types of currents mentioned in the beginning of this paper could be responsible for preparing the circumstances for the smaller type of current here dealt with. In this way we would be able to shorten the times of rest required for preparing the conditions for these currents. This appears important because it seems probable that, if there were conduction only, these periods would have to be longer than what actually appears to be the case.

There is still another feature which seems to point to large-scale convection reaching down over the full height of the mantle, but this system of currents, if the supposition is right, must have been working in the beginning of the Earth's history. The development in spherical harmonics of the topography at the Earth's surface which was published by Prey in 1922 shows a prevailing of the first order and of the third, fourth, and fifth order terms; the second-order term is somewhat less than the adjoining ones but is also considerable; the higher order terms are all much smaller. To obtain this result the writer has combined all the sub-terms of each order into one mean value representing the aggregate order term. (For this purpose the writer computed the mean of the squares of the total topography as given by the combined sub-terms of the same order and took the root of this mean value.)

It appears plausible to attribute the large first-order term and at least part of the second-order term (leading to the well-known particularity that one-half of the Earth's surface is much richer in continental areas than the other) to the release of the Moon which must have carried off a great amount of light matter from one side of the Earth. It could well be understood that when the Earth resumed its spherical shape the light matter did not entirely recover its regular distribution over the surface.

For explaining the prevailing of the third, fourth, and fifth order terms the writer has not been able to find another explanation than to assume convection currents in the mantle which have dragged together the sialic matter at the surface over the descending currents without dragging it downward. It can be proved that currents in the mantle extending downward over its total depth of 2900 km must mainly have been distributed according to third, fourth, and fifth order spherical harmonics, in fact exactly in the way as the surface topography shows it.

If we adopt this explanation of the fact that the continents and oceans appear to be distributed according to this mathematical system, we can only say that convection over the full depth of the mantle was likely at the beginning of the Earth's history; it does not prove that this is the case in more recent periods or at the present time.

Royal Netherlands Meteorological Institute,
De Bilt, Holland

REMARKS ON THE STRUCTURE OF THE MANTLE, AND ITS BEARING UPON THE POSSIBILITY OF CONVECTION CURRENTS

Francis Birch

All theories of geological processes must take into account such facts as we can establish concerning the present state of the Earth's interior. The principal source of quantitative information about the interior is seismology, but the results need analysis in the light of theories and experimental studies on the solid state. Two kinds of wave motion have been recognized; they are propagated with different velocities, V_P for the compressional wave, V_S for the shear wave, which have been determined as function of depth throughout the Earth. Analysis in terms of isotropic elasticity leads to the relation

$$V_P^2 - (4/3)V_S^2 = K/\rho = dP/d\rho \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (19)$$

where ρ is the density, K the coefficient of incompressibility (bulk modulus). The curve for K/ρ for the mantle is shown in Figure 17.

The variation of K/ρ may now be used to examine the question of uniformity. Here uniformity or homogeneity is taken to mean that the variations of properties (such as density and K) are caused by compression alone, as contrasted to variation resulting from chemical or phase change. If the density varies only with the pressure, and if the pressure distribution is approximately hydrostatic, so that $dP = -g\rho\,dr$, then we have the relation

$$dK/dP = 1 - g^{-1}d(K/\rho)/dr. \quad \ldots\ldots (20)$$

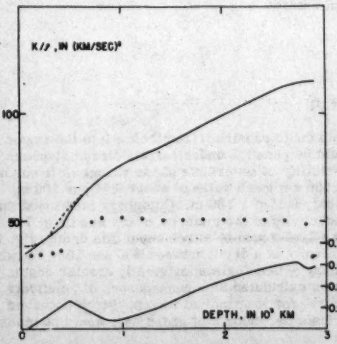


Fig. 17--Variation of K/ρ (upper curve) and of Poisson's ratio (lower curve) throughout the mantle, based on JEFFREYS' [1939] velocities (solid lines), and GUTENBERG's [1948] velocities (dashed line); for circles, see text

Here r is the radius, g the acceleration of gravity. Since g is nearly constant throughout the mantle, the quantity on the right may be formed directly from Figure 17, or better from the table from which this curve was plotted; this quantity may be said to be "observed." On the other hand, an equation of state [BIRCH, 1947] which is in excellent agreement with Bridgman's experimental compressions to 10^5 kg/cm^2 gives a theoretical curve for dK/dP as a function of depth, shown as a solid smooth curve in Figure 18. The "observed" points are in good agreement with the theoretical curve between about 900 km and the base of the mantle, but depart widely from this curve between depths of about 200 to 800 km. By this test, it appears that the lower part of the mantle is substantially uniform, while the upper part is not uniform. In other words, compression of a homogeneous material cannot account for the variation of dK/dP between 200 and 800 km; compression alone accounts very well for the variation of properties between 900 and 2800 km.

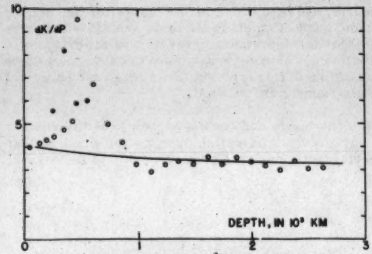


Fig. 18--The function $1-g^{-1}\,d(K/\rho)/dr$; open circles after JEFFREYS [1939]; solid circles after GUTENBERG [1948]; the solid line is the theoretical curve for dK/dP

A further step leads to the evaluation of K/ρ at zero pressure; such values corresponding to various depths are shown as circles in Figure 17, and provide an alternative demonstration of uniformity for the deep layer. The mean value of $(K/\rho)_0$ is 51 $(km/sec)^2$, and all points between 700 and 2800 km are within about one per cent of this. This K/ρ is about 50 pct higher than the corresponding figure for forsterite; if, as it is reasonable to believe, the lower part of the mantle is a ferro-magnesian silicate, this silicate must exist as a denser, more tightly bound structure than olivine, and may represent a high-pressure form of an olivine-pyroxene composition. There is no known silicate (except the implausible beryl) for which K/ρ approaches within ten per cent of the required value.

It should be realized that if this is indeed a new phase, as seems most probable, then we are for the moment ignorant of all except the elastic properties; we have no information concerning thermal expansion, adiabatic temperature gradient, melting point, or melting-point gradient, all quantities of theoretical importance. Some help may ultimately be forthcoming from the developing theories of the solid state.

The layer between about 200 and 800 km may be interpreted as a region in which transition to the high-pressure form takes place, probably with change of chemical composition as well. Above 200 km, there may be a thin uniform layer, but the seismic evidence for this region is still in dispute.

The most favorable region for convection thus seems to be the deep layer between 900 km and the base of the mantle. For so deep a circulation, however, it is necessary to meet a serious difficulty raised by BROOKS [1941], namely, that the time required for restoration by conduction of an initial temperature distribution, after an overturn involving the whole mantle, may considerably exceed the age of the Earth.

Between 200 and 800 km, circulation might be limited by the requirement of an exchange of latent heat, possible irreversibility of phase changes and intrinsic differences of density. It is not clear at present how serious any of these effects may be, but to assume unimpeded circulation in this region is to ignore its definitely transitional nature.

Harvard University,
Cambridge, Massachusetts

DISCUSSION

A discussion arose whether convection currents could penetrate from below into the region above 900-km depth. Griggs believed that this would be possible under certain circumstances; especially, it would be necessary to accept the possibility of reversible phase changes. It was observed that the geothermic gradient between 0 and 200 km has a value of about 0.5° per 100 m; between 900 and 2900 km it is much less, perhaps only 0.1° per 100 m. Gutenberg mentioned that Chapman and others found a change in electric conductivity of the material of the mantle at 700-km depth, and that this may be related to the change in dK/dP found by Birch about this depth (Fig. 18). The findings of Birch throw new light on the discontinuity at a depth between 900 and 1000 km which has been found from travel-time observations by many seismologists; originally greater depths (1500 km by Wiechert and Zoeppritz in 1906) had been calculated as a consequence of relatively small inaccuracies of the assumed time-distance curve for longitudinal waves. Birch observed that when there is a phase change, the change of volume per calorie of added heat would be much greater than when there is no such change.

Vening Meinesz expressed doubt whether there can be a shallow convection system between 20 and 200 km. During the following discussion he pointed out that in the three instances in which the direction of "faulting" in deep-focus earthquakes in the East Indies has been investigated the re-

sults indicate that the direction is reversed in deep-focus shocks with respect to that observed in shallow shocks. Gutenberg pointed out that field observations and records of shallow shocks seem to indicate that the bottom of the Pacific moves northward relative to the continent in California, Japan, the Philippines, and New Zealand.

THE HYPOTHESIS OF CONVECTION CURRENTS IN THE EARTH

J. H. F. Umbgrove

The hypothesis of convection currents in the Earth postulates homogeneity of the material in which the currents are supposed to occur. In this connection, the transition zone between 200 and roughly 900 km, to which Birch drew our attention, forms a serious problem. This zone represents either a change of phase, a chemical change, or both. If chemical change is involved, we have to give up the hypothesis of convection currents passing through this zone. If it is only a change of phase the problem remains whether Birch's results flatly oppose the hypothesis of convection currents over the entire 2900-km sector of the mantle, or whether there is a way out of the apparent difficulty. A positive answer to this question seems crucial with regard to any further discussion of convection currents.

Another problem is this: Change of phase involves change of volume of subcrustal matter; therefore, the question comes up "Is the Earth shrinking?" It would be of great importance if a quantitative estimate could be made in order to compare it with estimates of crustal shortening and Earth shrinking based on structural features of the Earth's crust.

What actually happens in the Earth's interior is probably not simply one single mechanical process. The problem has also its chemical and petrological aspects. Suppose a convection current transports peridotite material downward from, say, 60 km to a depth of 2900 km. Will its petrological properties remain unchanged under the temperature and pressure prevailing at that depth? And what becomes of the sialic matter of a deeply subsided part of the crust, as, for example, in deep basins and troughs? These are still baffling problems which also affect the hypothesis of convection currents.

It is to physicists that we owe a great advance of our knowledge of the Earth's interior; yet I feel that we urgently need also the cooperation of another group of scientists, namely, chemists and petrologists.

Institute of Mines,
Delft, Holland

DISCUSSION

P. P. Bijlaard (Cornell University, Ithaca, New York)--Birch found that between depths of 200 and 900 km the density increases rather rapidly, while between depths of 900 and 2900 km it is fairly constant. It might be possible that, as a consequence of differences in temperature, convection currents I between depths of 900 and 2900 km would occur, which might induce secondary currents II in the higher regions of the mantle, as sketched approximately in Figure 19.

Gutenberg pointed out that we observe at the surface phenomena which are possibly connected with convection currents at spots where the currents are going down (or coming up) and that all such observations refer to belts surrounding the Pacific basin.

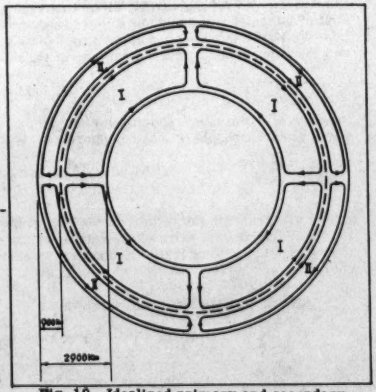


Fig. 19--Idealized primary and secondary convective currents in the mantle

Birch believed that the time constant for convection currents covering a layer 600-km thick would be of the order of 600 million years. It is possible that the convection currents in the mantle have produced the continents long ago, and that the continents have remained, whereas the direction of the currents since then has changed, so that they now may be rising below the continents. Goguel observed that the rising of plateaus is just as difficult to explain as the formation of basins.

Benioff mentioned results by Gutenberg and Richter indicating that in very large shallow earthquakes a special type of waves is found (G-waves, wavelength several hundred to over 1000 km) which may be absent in aftershocks. These long-period waves result perhaps from a readjustment in a large block, which in addition excites motions of shallow layers. Only the latter are observed in aftershocks.

Cox pointed out that astronomers may give help in investigations on convection currents and large-scale deformations of the Earth, since displacement of large masses must influence the rotation of the Earth.

ON SOME POSSIBILITIES OFFERED BY THE STUDY AT PLANETARY SCALE OF TERRESTRIAL PHENOMENA

J. F. Cox

The positions of the instantaneous axis of rotation of the Earth, by reference to the stars and also by reference to the Earth's crust itself, may be observed and represented by theory.

It seems that, on a planetary scale, astronomy will contribute more and more and has already contributed to problems related to movements in the interior of the Earth; it allows for closing conditions (errors of closure) or superior limits for astronomical effects related to internal displacements in the interior of the Earth, being detected either by changes in the rate of rotation of the Earth or variations of latitudes. The method allows for successive approximations and partition of periods.

It is well known that precession and nutation give figures for the flatness of the Earth to be compared with the values obtained in geodesy.

The method is fairly sensitive and with further development of clocks may give more and more interesting results; to show this, allowance may be made for the detection of seasonal fluctuations in the rate of rotation of the Earth (Stoyko, Finch) and the explanation of these fluctuations given by VAN DEN DUNGEN and Others [1949, 1950], LAURENT [1949-1950] working in a kind of informal collaboration with V. P. Starr of Massachusetts Institute of Technology. They take the Earth as composed of the crust (lithosphere), the oceans (hydrosphere), the atmosphere, and the core. The angular momentum of the system being constant, it may be written

$$\mathbf{M_A} + \mathbf{M_G} = \text{Constant} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (21)$$

in which $\mathbf{M_A}$ represents the angular momentum of the atmosphere and $\mathbf{M_G}$ the angular momentum of the globe (lithosphere + hydrosphere + core). The angular momentum $\mathbf{M_A}$ may be expressed by

$$\mathbf{M_A} = \iiint_{atm} \rho r \cos\phi \, (\omega r \cos\phi + v_x) \delta V \quad \ldots\ldots\ldots\ldots\ldots \quad (22)$$

where ρ represents the density of the air; r, the radius vector of a spherical Earth; ϕ, the latitude; ω, the instantaneous value of the rate of rotation of the globe; v_x, the zonal component of the wind (component along the parallel, from west to east); and δV, an elementary volume of the atmosphere.

VAN MIEGHEM [1950] has shown that

$$\partial \mathbf{M_A}/\partial t = \iint_{\Sigma} \tau_x^N r \cos\phi \cdot \delta\Sigma + \iint_{\sigma} (p_E - p_w) r \cos\phi \, d\sigma \quad \ldots\ldots\ldots\ldots \quad (23)$$

where τ_x^N is the zonal component of the tension due to friction of the surface of the globe on the adjacent layer of air, considering a unit of area which positive half normal N is directed towards the center of the Earth; Σ represents the total surface of the globe; p_E and p_w are atmospheric

pressures along the same parallel east and west from mountains; and σ is the surface limited by the profile of these mountains along a meridian section.

Now it is clear that

$$\partial M_G/\partial t + \partial M_A/\partial t = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (24)$$

but if it is accepted that the globe is solid (ω and $\partial\omega/\partial t$ the same at every place at the same time), it may be written that

$$\partial M_G/\partial t = J_G \; \partial\omega/\partial t \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (25)$$

J_G representing the moment of inertia of the globe. Substitution of (23) and (25) in (24) gives the value of $\partial\omega/\partial t$. If allowance is not made for v_x, it may be directly written that

$$\delta J/J + \delta\omega/\omega = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (26)$$

J being the moment of inertia of the globe, ω a mean value of the rate of rotation of the Earth.

Utilizing (26), VAN DEN DUNGEN and Others [1949, 1950] could allow for 20 pct of the fluctuation in the rate of rotation of the Earth by transfer of air masses, according to Napier-Shaw climatological maps, due allowance being made for altitude corrections. (This fact seems to have escaped attention of MUNK and MILLER [1950] in their criticism.) The calculated phases are in accordance with the observed ones; the phenomenon appears to be related also to the annual component of the variation of latitudes.

Utilizing (23), (25), and (24), the authors find a good representation of the observed facts with the supplementary hypothesis of an annual compensation in the transfer of momentum from the atmosphere of one hemisphere to the other.

Free University of Brussels,
Brussels, Belgium

DISCUSSION

Nadai asked whether there is evidence of observable changes of longitude. Vening Meinesz answered that measurements of 1927 and 1935 have not yet given any definite results. The measurements will be continued, since longer periods may bring out changes which are too small to be detected by comparison of the data available thus far. Annual changes of latitude must of course be eliminated, in order to obtain conclusive data. Bullard pointed to the difficulty of observation in this respect: One can measure changes of the moment of momentum of one in 10^8; this would correspond to a few cm thickening of the Earth; one must suppose that convection currents would have much less effect. Cox also mentioned that perhaps one could look for a correlation between earthquakes and changes of the time of rotation.

Bullard pointed out that the secular variation of the Earth's magnetic field might be connected with convection currents in the fluid core of the Earth. In the following discussion as to whether the Earth is cooling or is getting warmer, Bullard mentioned that in his opinion a temperature of 1000° to 2000° for the core would best explain the present conditions.

Glangeaud then drew attention again to the importance of thermodynamic conditions and of polymorphic transformations, like those of α to β quartz. In the transition region the quartz has peculiar properties; for instance, if one adds Fe_2O_3, this can penetrate into the quartz and make the transformation irreversible. Umbgrove added that it is useful always to keep in mind that the convection currents involve petrological problems.

FLUID MOTION OF EARTH'S INTERIOR AS INFERRED FROM GEOMAGNETISM

E. H. Vestine

Changes in the geomagnetic field may imply changing fluid motions within and near the surface of the Earth's central core. These fluid motions may in fact cause the field and its changes by dynamo action, according to ideas developed by Larmor, Elsasser, and Bullard.

The Earth's field, with a number of irregularities and areas of rapid change in fields of continental extent, appears to have been moving westward at a rate of about 0.2° of longitude per year during the past 100 years. This may be evidence of a westward motion of the surface of the core relative to the mantle of the Earth. By the use of simple and somewhat coarse model representations of the field, for example, an eccentric dipole about 300 km from the Earth's center, it is found that this dipole would have appeared to have been moving westward and slightly northward since the year 1500. Evidence prior to 1500 is being studied. The data comprise measurements on early baked pottery and bricks which include magnetite, magnetized in the direction of the Earth's field by cooling through the Curie point at the time of their making.

When Earth materials including small amounts of ferromagnetic particles cooled through the Curie point, or when such particles are deposited in water to form sediments or clays, the material acquires a direction of magnetization paralleling the Earth's field at the time of deposition. Graham has found that such paleomagnetism is probably preserved in Silurian sediments laid down nearly 400,000,000 years ago, by noting that segments of such rock folded near that time show today a uniform direction of magnetization after "unfolding" in the laboratory. Other measurements of the magnetization of varved clays and sedimentary rocks show that the Earth's field has undergone considerable fluctuations sometimes continuing for a few thousand years in the same sense in remote history. It may hence be ultimately possible to draw reasonable conjectures respecting fluid motions within the Earth's central core during a considerable interval of the Earth's history

The variation of electric conductivity of the Earth at depths of 400-1000 km has been inferred from the electromagnetic induction due to varying electric currents flowing outside the Earth. Knowledge of the surface magnetic field alone suffices to determine the part of the field of external and internal origin. The relative amplitude of these fields, together with their relative shifts in time phase, permits estimates of electric conductivity as a function of depth. It seems likely that existing data on frequent pulses of the geomagnetic field enduring for some minutes will extend these results to shallower depths. In this way, in view of the relationship of electric conductivity and temperature, information useful in constructing convection theories of the crust may be forthcoming, especially if there can be established a difference in the electric conductivity between the material under ocean and continental areas

Department of Terrestrial Magnetism,
Carnegie Institution of Washington,
Washington, D. C.

DISCUSSION

E. C. Bullard (National Physical Laboratory, Teddington, England)--There is some evidence for the existence of convection currents in the mantle from the theory of the Earth's magnetic field. It is widely accepted that the origin of the secular variation lies in motions in the outer part of the core. Only in this way can one understand the rapidity of the change and its independence of geography and geology. The only plausible cause that has been suggested for motions in the core is thermal convection. For thermal convection to occur, enough heat must be generated in the core and removed at its surface to maintain a temperature gradient in excess of the adiabatic gradient. The generation of the heat presents no insuperable difficulty, but its removal from the surface would be difficult to account for if only thermal conduction is available to transport it through the mantle. This problem is greatly simplified if we can suppose convection currents to exist deep in the mantle. The motions in the mantle are certainly too slow to have direct magnetic effects. It is possible, however, that the temperature differences associated with them may affect or control the motions in the core and thus indirectly influence the magnetic field.

In connection with the observations on magnetic fields dating from geological distant periods, Vening Meinesz asked whether one must assume that magnetization of the rocks has been "frozen in" at their formation and that since then there has been no change. This seems to be the case, but Bullard pointed out that there are dykes in Scotland, South Africa, and New Zealand where the magnetization often seems to have the wrong direction.

SUMMARY
COLLOQUIUM ON PLASTIC FLOW AND DEFORMATION WITHIN THE EARTH

B. Gutenberg

L. H. Adams started the Colloquium by presenting the history of the meeting. This was followed by a summary by J. M. Burgers of terms used in describing rheological phenomena (deformation and flow). The importance of time dependence in these phenomena was stressed and attention was directed to the necessity of clearly distinguishing between recoverable and non-recoverable deformations. Experiments should be performed in such a way that it will be possible to find the magnitude of the permanent deformation after unloading, with due precautions to allow slow recovery phenomena to reach equilibrium. A number of examples of flow diagrams were discussed. The term plastic deformation is reserved for those cases where permanent deformations, of a magnitude large compared with the recoverable part of the deformation, appear only when the stress exceeds a certain threshold value, called the yield value. A discussion followed this lecture.

Most findings and definitions concerning non-elastic processes are based on laboratory experiments involving metals under strain. The rather scanty results concerning rocks, including the relatively large effects of temperature and water content, were discussed by David Griggs. Francis Birch mentioned the different behavior of materials in the form of cylinders depending on whether they are enclosed or not enclosed.

W. H. Bucher introduced the subject of folded belts, which can be studied better than any other geological form and give indications of the processes which have been going on in the past. Sedimentary layers at the Gulf of Mexico, which he discussed as an example, have their greatest thickness under the edge of the shelf. The upper layers, as far as they can be found, dip towards the Gulf side without appreciable change in slope. Bucher then discussed crustal shortening.

P. P. Bijlaard spoke about patterns of flow lines in experiments and their importance for interpretation of a number of phenomena. Edward Bullard returned to the problem of the amount of the Earth's contraction and the "stretching" of mountains, which is necessary to find the original width of the crustal area which has been folded. He agreed with Jeffreys, who has pointed out that mountains were not folded similar to the way in which a sheet of paper or a thin sheet of metal folds under pressure in the direction of one of the longer dimensions. Consequently, one does not find the original dimensions of the layers which formed the mountains by stretching and unfolding them. One rather has to consider the total mass which is stored in the mountains. In this way a much smaller amount of compression results than from straightening the folded surface layers.

W. Heiskanen discussed density distribution and possible forms of cross sections through the various layers contained in the belts near the shelf border. In a discussion of geosynclines, Jean Goguel made some remarks on the pressure pattern. Griggs pointed out that there are three principal types of processes which may cause geosynclines. The first type involves a process in which the material down to a relatively great depth is compressed and moves downward. The second possible cause is subcrustal currents, which move downward below the central part of the syncline. The third possible explanation is connected with a process (possibly as a consequence of tension or erosion) in which the upper part of the crustal layer bends downward and the lower boundary upward. In this case, we would not have any great gravity anomalies, while in the other two cases one should have considerable negative gravity anomalies.

Burgers then pointed out that extrapolation from results found by use of small relatively homogeneous samples to the large dimensions involved in the problems concerning the Earth must be done very carefully.

M. L. Glangeaud discussed two types of mechanism of mountain formation. On the Pacific side the surface layers consist of sima (ultra-basic material) containing water, and in the continents of granite with water content and sial. Between the two are the orogenic belts. Glangeaud pointed out that conditions and processes (for example, heat flow) on the two sides of this orogenic belt differ widely and that this results in a horizontal energy gradient across the boundary. The mountain ranges following the belt along the boundary between the Pacific and the surrounding continents (liminary zones) may have been formed mainly as a consequence of energy gradients. Temperature gradients may result in chemical processes and convection currents.

Hugo Benioff discussed results found in the study of energy release or displacements in earthquakes. In aftershocks of earthquakes the accumulated energy or the accumulated displacement shows different patterns, some of which can be explained by shear, others by compression. He then pointed to patterns related to energy release over larger areas. It is astonishing how smooth the curves are which are obtained in this way, if shocks along the whole length of the fault are used. In some areas (for example, the Tonga area) the deep shocks and the intermediate shocks show separately similar patterns which can be combined, while in other regions (for example, in South America) the two show quite different patterns, although the years in which one pattern changes into a different pattern are approximately the same. However, there is little correlation between the pattern indicated by shallow earthquakes and those by the deeper earthquakes.

Heiskanen discussed the uplift of Fennoscandia and the conditions before, during, and after the glacial period. During the early stage when the iceload depressed the crust there must have been outward subcrustal currents, while at present (movements upward to restore equilibrium) there must be inbound subcrustal currents. The results calculated from gravity anomalies and those from the actually observed uplift agree in general. Bijlaard pointed out that the horizontal dimensions of the area involved are so large compared with the thickness of the lithosphere that the crust would present negligible resistance to working of this type.

Heiskanen mentioned regions (for example, in Central Europe) having a width of over a thousand miles with average gravity anomalies of +30 milligals, and others (for example, in Asia) with anomalies -30 milligals. During the following discussion, Bijlaard remarked that a finite strength in the uppermost crust (say, above sea level) and lateral horizontal forces against the mountains are necessary to press the mountains upward and to maintain them.

Griggs introduced the problem of convection currents. If the thermal gradient is in excess of the adiabatic gradient throughout the mantle, by an amount of, say, 300° C, convection currents may result. They may have various patterns, such as with two cells and four cells, extending all the way down to the core, or extending only to a certain depth or operating only below a certain depth.

H. H. Hess discussed the belts with relatively large gravity anomalies along the arcs in the western Pacific and the belt in the West Indies which extends into South America; he sketched the distribution of shallow and deep earthquakes, ocean deeps, and other phenomena along these arcs, and the frequent presence of peridotite along the belts of negative gravity anomalies. This peridotite must form during the early time of the process when the bulging down of the central part occurred and when the sialic material came in connection with the deepest simatic material there. In addition to peridotite, metamorphic rocks frequently occur along the belts of negative anomalies.

Griggs described his models which simulate the processes in convection currents near the surface.

Birch spoke on his recent investigations. The ratio of the bulk modulus (the reciprocal of the compressibility) over the density is a quantity which can be calculated directly from the earthquake velocities, but also can be found for homogeneous materials from laboratory experiments. He pointed out that between the bottom of the continental layer (the Mohorovičić discontinuity) and a depth of about 200 km this quantity is practically constant, as one has to expect in homogeneous materials. But between a depth of about 200 and 900 km this quantity is much larger than for any known material. It changes considerably in this depth interval, indicating that there are changes in the material or in its phase. From a depth of 1000 km down to the core the ratio of the bulk modulus to the density, as well as the derivative of the bulk modulus with respect to pressure, are almost constant, indicating that we may have here again a homogeneous material. As a consequence of changes in phase or kind of material at depths between 200 and 900 km, convection currents can hardly be expected to cross this depth range. In the lower part of the mantle, the ratio of the bulk modulus to the density corresponds to what one would have to expect, for example, for diamond or carbides under the conditions there. The corresponding ratio calculated from seismic velocities for the upper mantle below a depth of 200 km is appreciably higher than one would expect in known types of rock, considering the effect of pressure. The material there must be a phase with higher binding than in peridotite or olivine under surface conditions. Birch considered it possible that the limitation of earthquakes to the upper 700 km of the mantle is related to these conditions.

F. A. Vening Meinesz gave a summary of geophysical processes in the East Indies. He con-

tinued with a discussion of convection currents. The direction of movement has been studied for only three deep-focus earthquakes in the East Indies, but in all three the resulting direction was found to be reversed relative to that observed in shallow shocks. Beno Gutenberg pointed out that the field observations and records of shallow shocks seem to indicate that the bottom of the Pacific moves northward relative to the continent in California, Japan, the Philippines, and New Zealand.

Vening Meinesz continued to discuss convection currents with one or more cells. He also pointed to the importance of the results of Prey, who calculated coefficients of spherical harmonics to represent the surface topography of the Earth up to terms of the 16th order. The first four terms are especially large. The term of the first order indicates the difference between the continental half sphere and the oceanic half sphere.

After an extended discussion on convection currents, J. F. Cox pointed out that differences of the Earth's rotation between summer and winter have been established. They may be explained by changes of momentum due to annual fluctuations of air masses, air, water, and similar influences.

Vening Meinesz and Cox discussed relative displacements of parts of the Earth's crust, especially of Greenland relative to Europe, which were supposedly larger than observational errors. However, it was pointed out that during recent observations with more accurate methods and means no movements of continents have been observed.

Vening Meinesz stated that currents in the mantle are expected to be very slow but that currents in the core may be much faster. Bullard discussed in more detail the importance of currents in the core for the explanation of terrestrial magnetism. There are certain energies needed to maintain these currents in the core, since otherwise the electromagnetic forces would stop in about two years. The source required to maintain these currents may be radioactive heat. Large-scale convective currents may remove some of the heat. In a discussion whether the Earth is cooling or getting warmer, arguments in favor of both possibilities were mentioned, but no conclusion was reached. Bullard stated that in his opinion a temperature of 1000° to 2000° for the core would agree best with the present theories and information.

Glangeaud referred to observations by glassmakers that in their containers local currents occur in places where the glass forms or exists. These local currents may be of a type similar to convection currents which may exist near the continental borders. Polymorphic transformations are of great importance for this problem, for example, the transition of α-quartz to β-quartz. There are phase transitions other than those of quartz in the mantle which are of similar importance.

E. H. Vestine pointed out that the magnetic center of the Earth is a few hundred kilometers distant from the actual center and that it is moving in course of time on a path leading at present slightly away from the center; it also has a noticeable horizontal component. Measurements of the magnetization during Silurian and afterwards show that the field has changed back and forth with periods of 1000 years up to 50,000 years, but that there is no indication for a systematic change since Silurian. Bullard stated that the center dipole stays about where it is, but that disturbances move and produce the observed changes of the Earth's magnetic field.

Finally, Heiskanen came back to his previous mention of large areas with positive or negative gravity anomalies of about 30 milligals, and indicated that differences in density which are required to explain them are small if they extend to depths of 100 or even several hundred km. Vening Meinesz raised the question how in such a case the equilibrium is maintained. Gutenberg emphasized that most of the anomalies mentioned by Heiskanen are along or adjacent to seismic belts. Consequently, no equilibrium can be expected there at present and no differences in density below a depth of about 60 km have to be assumed.

After some concluding words by Vening Meinesz, Gutenberg mentioned that conferences on the interior of the Earth are being prepared for the General Assembly of the International Union of Geodesy and Geophysics to be held in Brussels in 1951.

The thanks of all participants were then expressed to L. H. Adams and to E. G. Fullinwider for their organizational and administrative work.

Seismological Laboratory,
California Institute of Technology,
Pasadena, California

References (for entire Colloquium)

BENIOFF, HUGO, Seismic evidence for the fault origin of oceanic deeps, Bull. Geol. Soc. Amer., v. 60, pp. 1837-1856, 1949.

BENIOFF, HUGO, Earthquakes and rock creep, Bull. Seis. Soc. Amer., v. 41, pp. 31-62, 1951.

BIJLAARD, P. P., Beschouwingen over de knikzekerheid en de plastische vervormingen van de aardkorst in verband met de geologie van den Oost Indischen archipel, De Ingenieur in Ned. Indie, v. 2, no. 11, pp. 1135-1156, 1935.

BIJLAARD, P. P., Théorie des déformations plastiques et locales par rapport aux anomalies négatives de la gravitation, aux fosses océaniques, aux géosynclinaux, au volcanisme, à l'orogénie et à la géologie de l'océan pacifique occidental, Assn. Géodesie, Congrès d'Edinbourg, 1936a.

BIJLAARD, P. P., Nadere toelichting van de toe passing van mijn theorie der plaatselijke plastische vervormingen op de tektoniek, Ing. Ned. Indie, no. 11, pp. 1160-1170, 1936b.

BIJLAARD, P. P., A theory of plastic buckling with its application to geophysics, Proc. Kon. Akad. Wetensch., Amsterdam, v. 41, no. 5, pp. 468-480, 1938.

BIJLAARD, P. P., Theory of local plastic deformations, Pub. Internat. Assn. Bridge and Struct. Eng., Zurich, v. 6, pp. 27-44, 1940-1941 (summary of the author's earlier papers in De Ingenieur, 1931, 1933, and in De Ingenieur in Ned. Indie, 1935, 1936, 1939).

BIJLAARD, P. P., On the linear patterns of the Earth's crust, Proc. Kon. Akad. Wetensch., Amsterdam, v. 51, no. 4, pp. 450-456, 1948.

BIJLAARD, P. P., Theory and tests on the plastic stability of plates and shells, J. Aeronautical Sci., v. 16, no. 9, pp. 529-541, 1949.

BIRCH, FRANCIS, Finite elastic strain of cubic crystals, Phys. Rev., v. 71, pp. 809-824, 1947.

BRIDGMAN, P. W., Volume changes in the plastic stages of simple compression, J. Appl. Phys., v. 20, pp. 1241-1251, 1949.

BROOKS, H., Cyclic convection currents, Trans. Amer. Geophys. Union, pt. 2, pp. 548-551, 1941.

BUCHER, WALTER H., The pattern of the Earth's mobile belts, J. Geol., v. 32, pp. 265-290, 1924.

BUCHER, WALTER H., The deformation of the Earth's crust, Princeton Univ. Press, 1933.

BUCHER, WALTER H., The deformation of the Earth's crust, Bull. Geol. Soc. Amer., v. 50, pp. 421-431, 1939.

BUCHER, WALTER H., Megatectonics and geophysics, Trans. Amer. Geophys. Union, v. 31, pp. 495-507, 1950.

BURGERS, J. M., and G. W. SCOTT BLAIR, Report on the principles of rheological nomenclature, pub. Joint Committee on Rheology, Internat. Coun. Sci. Unions, Amsterdam, 1949.

GRIGGS, DAVID, Creep of rocks, J. Geol., v. 47, pp. 225-251, 1939a.

GRIGGS, DAVID, A theory of mountain building, Amer. J. Sci., v. 237, pp. 611-650, 1939b.

GUTENBERG, B., On the layer of relatively low wave velocity at a depth of about 80 km, Bull. Seis. Soc. Amer., v. 38, pp. 121-148, 1948.

GUTENBERG, B., and C. F. RICHTER, Earthquake magnitude, intensity, energy and acceleration, Bull. Seis. Soc. Amer., v. 32, pp. 163-191, 1942.

GUTENBERG, B., and C. F. RICHTER, Seismicity of the Earth and associated phenomena, Princeton Univ. Press, 1949.

HASKELL, N. A., The motion of a viscous fluid under a surface load, Physics, v. 6, pp. 265-269, 1935.

HESS, H. H., Major structural features of the western North Pacific, an interpretation of H. O. 5485 Bathymetric Chart, Korea to New Guinea, Bull. Geol. Soc. Amer., v. 59, pp. 417-446, 1948.

JEFFREYS, HAROLD, The times of P, S, and SKS, and the velocities of P and S, Mon. Not., R. Astron. Soc., Geophys. Sup., v. 4, pp. 498-533, 1939.

KÄÄRIÄINEN, ERKKI, Beiträge zur Landhebung in Finnland, Veröff. Finn. Geod. Inst., no. 36 (Bonsdorff Volume), p. 92, 1949.

LAURENT, MARIETTE, Sur les fluctuations de période annuelle de la rotation de la Terre, Bull. Acad. R. Belg., Cl. Sci., v. 35, 1949; v. 36, 1950.

LEON, ALFONS, Der Bauingenieur, v. 15, no. 31, 32, 1934; also Proc. 4th Internat. Cong. Appl. Mech., Cambridge, England, 1934, and Ing. Archiv, v. 4, p. 421, 1933.

MICHELSON, A. A., Elastico viscous flow, pt. 1, J. Geol., v. 25, pp. 405-410, 1917; pt. 2, v. 28, pp. 18-24, 1920.

MUNK, W. H., and R. L. MILLER, Variation in the Earth's angular velocity resulting from fluctuations in atmospheric and oceanic circulation, Tellus, v. 2, p. 2, 1950.

NADAI, A., On the creep of solids at elevated temperature, J. Appl. Phys., v. 8, pp. 418-432, 1937.

PEKERIS, C. L., Thermal convection in the interior of the Earth, Mon. Not. R. Astron. Soc., Geophys. Sup., v. 3, pp. 343-368, 1935.

STILLE, HANS, Geotektonische Probleme des pazifischen Erdraumes, Preuss. Akad. Wiss., Abh., Math.-nat. 6, no. 11, 1944.

TANNI, L., On the continental undulations of the geoid as determined from the present gravity material, Pub Isost. Inst., no. 18. 1948.

TAYLOR, NELSON W., Mechanism of fracture of glass and similar brittle solids, J. Appl. Phys., v. 18, pp. 943-955, 1947

TIMOSHENKO, S., Strength of materials, second ed., p. 468, 1941.

VAN DEN DUNGEN, F. H., J. F. COX, and J. VAN MIEGHEM, Sur les fluctuations de période annuelle de la rotation de la Terre, Bull. Acad. R. Belg., Cl. Sci., v. 35, pp. 642-655, 1949.

VAN DEN DUNGEN, F. H., J. F. COX, and J. VAN MIEGHEM, Sur les fluctuations saisonnières de la rotation du Globe terrestre, Bull. Acad. R. Belge, Cl. Sci., v. 36, 1950.

VAN MIEGHEM, J., Troisième Congrès National des Sciences, Brussels, June, 1950.

VENING MEINESZ, F. A., Gravity expeditions at sea, Netherlands Geod. Comm., v. 2, Delft, 1934.

VENING MEINESZ, F. A., Earth's crust deformation in geosynclines, Proc. Kon. Ned. Acad. Wetensch., v. 53, pp. 27-46, 1950.

WEGMANN, EUGENE, Transformations metasomatiques et analyse tectonique, 18th Internat. Geol. Congr., 1948, pt. 3, pp. 45-52, 1950.

(Communicated manuscript received March 30, 1951;
open for formal discussion until January 1, 1952.)

Transactions, American Geophysical Union Volume 32, Number 4 August 1951

RADAR ALTIMETRY OPERATIONS OF THE UNITED STATES GEOLOGICAL SURVEY IN 1950

Julius L. Speert

(Published with the permission of the Director, U. S. Geological Survey)

Abstract--This paper describes the methods employed in obtaining ground elevations for topographic mapping by the use of an airborne radar altimeter and related equipment. The 1950 program of the U. S. Geological Survey in Alaska is described and some of the results obtained are presented and discussed.

Introduction--In 1950 the United States Geological Survey undertook what is believed to be the first attempt in the United States to obtain ground elevations for topographic mapping by airborne electronic methods. The work was done for the Survey, under contract, by Photographic Survey Corporation, Ltd., of Toronto, Canada, and its affiliated company, Kenting Aviation, Ltd., using the Airborne Profile Recorder (APR). Approximately 78,000 sq mi in central Alaska were covered on this project.

Radar altimetry--The problems of obtaining ground elevations by radar altimetry are in many respects very similar to the more familiar problems of hydrographic surveying. In the latter operation, a boat sails along the surface of the ocean, and the elevation of points along the bottom are measured with respect to the sea-level surface. These depth measurements may be made with a lead line or with more modern echo-sounding equipment. If there is any appreciable wave action to cause the boat to ride above or below the average reference surface, it is desirable to have a means of measuring such deviation from the mean reference level. Similarly, the effects of tidal variations during the period of measurement must be determined, so that proper corrections may be applied to compensate for the tidal changes. And finally, a position fix must be made so that the location of each sounding may be determined in its relationship to other soundings and to fixed features, such as the shore-line. Modern sounding apparatus actually plots a profile of the bottom over which the boat sails.

In surveying over land, it is obviously impossible to sail along an ocean surface. The best available substitute is to fly an airplane at a constant altitude above sea level, and then apply a correction to the measurements to compensate for the height of this reference surface. The best approach to a constant-level surface in the air is the isobaric surface, that surface at which the barometric pressure is constant. The elevation of this isobaric surface is determined at the beginning and end of each run, not by a barometric altimeter, but by flying over the ocean surface, or a ground or lake surface of known elevation, and measuring the height of the airplane above this known elevation with the radar altimeter. Then, as the airplane flies the assigned course, soundings are made to ground points below it with the radar altimeter in the same way that echo soundings are made in water. As in modern hydrographic surveying, a continuous profile of the ground under the flight path is recorded automatically on a moving tape.

Since currently available aircraft cannot fly a perfectly level course, the deviations from the nominal level surface are analogous to wave action. With APR, these deviations from a pre-set pressure level are measured by a sensitive aneroid capsule. The deflections of this capsule from its pre-set position control an electronic circuit through a variable-capacitance condenser, and feed correcting signals into the profile recorder to compensate automatically for the deviations from the nominal pressure level to which the aneroid capsule has been set. The recorded profile is thus referred automatically to the nominal flying height and not to the actual, erratic flying height.

Because of continual atmospheric changes, the isobaric surface is neither a true plane, nor level, nor at a constant altitude above the sea. It is shifting continuously in the same way, but not according to the same laws, as the sea-level surface shifts with the tides. Meteorologists have demonstrated that the predominant upper-level winds are related to the tilt of the isobaric surface. These same winds affect the navigation of the aircraft to produce the drift that is so familiar to all pilots and navigators. Formulas have been developed by which it is relatively easy to compute the average slope of the isobaric surface along portions of the flight path from a knowledge of the

drift angles observed in those portions of the flight. Drift-meter readings are made periodically in flight, and the resulting computed corrections are applied to the elevations of the profile graph.

After all these corrections have been applied, there is still likely to be a closure error in the check reading at the end of the flight. This final closure error is prorated linearly to all points along the flight path to determine the final values for the elevations above sea level.

As with hydrographic soundings, the elevations or profiles are of little value unless they can be located in position with respect to known features. To relate the APR profile to the ground to which it applies, overlapping vertical photographs are obtained along the flight path at the time the profile is obtained, and a tick is recorded on the margin of the profile graph at the instant of each exposure.

Equipment--The APR altimeter employed on this project uses a wave length of 3.2 cm and has a four-foot parabolic reflector. The effective beam width is about 1.5°. The vertical photographs were taken with a specially constructed 35-mm camera having a minimum coverage of 63.5° and with its principal point accurately etched in the optical system. The ground profiles and the deviations from nominal flying height were recorded with an Esterline-Angus recording milliammeter. The aircraft used was a Lockheed Hudson, carrying a crew of five men.

Central area--In the original plans for the project, it was hoped that profiles could be obtained that would be suitable for controlling mile-to-the-inch maps with a contour interval of 100 ft in an area where we had good Shoran-controlled vertical photography, obtained for us by the Air Force in 1949. It was planned to fly these profiles, approximately eight miles apart, across the photographic flight lines, so that the eight-mile distance between the profiles could be bridged with multiplex. It was not expected that the entire portion of the profile would be usable, but it was hoped that enough features could be selected from each, such as water surfaces, flat land areas, and ridge and valley crossings, so that spot elevations could be obtained to control the multiplex models. Accordingly, it was planned to permit each profile path to deviate slightly from a straight line to pick up any such features that might be near the planned route.

Since no previous experience existed on this kind of work, there was no assurance as to the accuracies that could be obtained other than the contractor's claims. Partly to check the accuracy of the equipment and proposed technique, and also to provide control elevations for the ends of the parallel profiles, control flights were planned to encircle the area over which the profiles were to be obtained. The control routes were to be flown three or more times. On each flight, elevations were to be determined for designated lakes, river crossings, and flat sections of land. These features were selected so that the elevations of many of them could be checked by ground methods from bench marks that had been established previously not too far away. It was stipulated that the total spread of the three or more elevations determined for any feature should not exceed 20 ft. Of 22 elevations so determined, all satisfied this requirement of having not more than a 20-ft spread, the average spread of the readings being 11 ft.

It was further stipulated that the average of the several elevations determined for each feature should check the ground-survey determination within a tolerance of $\pm (10 + 2\sqrt{M})$ ft, where M is the distance in miles from the nearest check point or from the start of the run. Of 14 elevations so checked, all were well within this limit. The maximum error was +23 ft at a distance of 114 mi from the check point, where a tolerance of 31 ft was allowed; the average error, without regard to sign, was less than ten feet.

With this indication of the accuracy of the method, the parallel profiles were flown, once each, by the same technique, using the control-flight features as starting and check points. Some of these profiles overlap an area that was being mapped simultaneously with ground control. The compilation manuscript on some of the new quadrangles has now reached the point where direct comparison should be possible between the radar profiles and the map manuscript. This comparison has not been made yet, but is planned for the very early future.

Reconnaissance area--Since there was no assurance at the planning stage of the project that the results would be suitable for 100-ft contouring, and since vertical control was urgently needed for compiling and revising our series of 1:250,000 scale maps with contour intervals of 200 ft and greater, the same project was extended to include surrounding areas, but the specifications were relaxed somewhat because of the less exacting requirements of this type of mapping. The control flights were to be flown twice, with a permissible spread of 30 ft, and the tolerance on absolute elevation checks was increased by 50 pct. The profile spacing was increased to 16 mi to obtain greater coverage. Since no vertical photography was available yet for most of this area, the profiles were flown in the most convenient direction, generally across the prevailing drainage pattern.

Of 29 control elevations examined in the reconnaissance portion of the project, only one feature exceeded the allowable spread of 30 ft. Four runs over this feature showed a total spread of 44 ft, but three of the readings fell within a spread of 24 ft. One reading was obviously bad. Except for this feature, the maximum spread was 26 ft, and the average spread was 14 ft. Unfortunately, there were no opportunities to check the absolute elevations of any of the control features in this area.

One major question arose in connection with the planning of this project. How many useful elevations can be obtained from each profile? Obviously, a side slope or the crossing of a sloping ridge would be of little value because of the difficulty of accurately identifying the exact point on the ground that the profile elevation applied to. Water features and crossings of broad valleys or gently sloping streams are easily identified and are useful. A study made of one block of profiles covering both level and hilly country indicated that usable elevations could be obtained at an average spacing of about ten miles.

In one block, two cross profiles were flown across the parallel profiles to check their internal accuracy and consistency. Of 15 identified common points on the regular profiles and the cross profiles, the elevation agreements varied between eight feet and 50 feet, with a mean difference of 26 ft.

Plans are in progress now to evaluate the usefulness of the profiles in map compilation by compiling a 1:250,000 scale quadrangle stereoscopically from existing trimetrogon photography, using only the APR data for vertical control. A quadrangle has been selected for this test where good horizontal control is available in one corner of the area, with no horizontal control in the remainder. The area has some relatively flat sections and some heavy relief; it includes some of the eight-mile profiles and some of the 16-mile profiles. In addition, several mile-to-the-inch sheets in this area have already been completed through the compilation stage and may be used to test the proposed 1:250,000 scale compilation.

Oblique photography--At the same time that the profiles were being flown, oblique photographs were taken with a calibrated survey camera at intervals of three to four miles along the flight path. The oblique camera, of six-inch focal length, with nine- by nine-inch negative, was mounted in the nose of the plane, pointing forward, with a depression angle of 30°. Exposures of the oblique camera were accurately synchronized with corresponding exposures of the 35-mm vertical camera and with the profile graph. Although the oblique photography was not an integral part of the radar altimetry project, it is hoped that the oblique pictures will be of considerable help in evaluating the accuracy and consistency of the profiles and will permit extending control elevations by vertical angle measurements on the photographs to additional features not directly along the flight paths.

Accomplishment--About 15 days of flying weather were available for this project between the end of June and the beginning of October. Almost 9000 mi of record flying was obtained, of which about 5800 mi were formal profiles. The remainder, over 3000 mi, were required for the control flights.

Topographic Division,
U. S. Geological Survey,
Washington, D. C.

(Manuscript received April 9, 1951; presented at the Thirty-Second Annual Meeting, Washington, D. C., May 2, 1951; open for formal discussion until January 1, 1952.)

Transactions, American Geophysical Union Volume 32, Number 4 August 1951

THE INFLUENCE OF GROUND CONDITION AND CLOUDINESS ON THE DIURNAL MARCH OF SURFACE VAPOR PRESSURE AT BLUE HILL, MILTON, MASSACHUSETTS

Photios P. Karapiperis

Abstract--Four types of diurnal march of vapor pressure are recognized as being related to the availability of water vapor and the intensity of turbulent mass-exchange associated with thermal convection: oceanic, with a march parallel to that of temperature; continental, with a double oscillation featured by a primary minimum at sunrise and a secondary one in the afternoon; steppe, with a double oscillation having the primary minimum in the afternoon; and desert, with a march essentially opposite to that of temperature, but lagging a few hours behind. The vapor pressure at Blue Hill has a diurnal march of the oceanic type when the ground is snow-covered or the sky is overcast; also, the marches for the months of January and July are essentially oceanic. The continental type is found when the sky is clear and the ground is moist, and also in the averages for April and October. The steppe type occurs when the sky is clear and the ground is dry or is bare and frozen.

Introduction--The actual amount of water vapor per unit volume can be expressed in grams per cubic meter (gm/m^3) and this ratio is called absolute humidity. Another equivalent measure, more commonly used, is the vapor pressure, expressed in mb, mm, or inches of mercury. Besides the temperature, which limits the maximum vapor pressure, other controls are the distance downwind from bodies of water, the surface temperature and size of such bodies, the intervening topography, the direction and velocity of the wind, the moist or dry condition of the ground, the cloudiness as affecting the insolation, and the turbulent mass-exchange. The effect of air-mass type on moisture content is not considered here, since averages are computed in which all air masses occur.

The diurnal march of vapor pressure is a function of several factors. The diurnal minimum temperature almost invariably produces a minimum in vapor pressure at the same time by limiting the vapor to the maximum possible at that low temperature. A rise in vapor pressure accompanies the morning rise in temperature as dew evaporates. A fall usually sets in before noon, however, owing to the turbulent mass-exchange, which transports water vapor from its source, the surface of the ground, to higher altitudes and brings down dry air from aloft. Mass exchange is greatest in the afternoon because wind velocity and thermal convection are then strongest. This fall is the greater the stronger the turbulent mass-exchange and the smaller the quantity of moisture evaporating from the surface.

Diurnal marches of vapor pressure have been divided [CONRAD, 1936] into three types: oceanic, continental, and steppe and desert. In the oceanic type there is an abundance of water always available, so the march of vapor pressure parallels that of the air temperature. In the steppe and desert type, there is little or no water available, so the march of vapor pressure is dominated by the turbulent mass-exchange, and thus is essentially opposite to the march of temperature. The continental type is a double-oscillation mixture of the two, with main minimum at time of temperature minimum, main maximum in the evening, secondary maximum in the forenoon, and secondary minimum in the afternoon at about maximum temperature.

It would seem desirable to subdivide the steppe and desert type into the steppe type for a double oscillation similar to that of the continental type, but with the afternoon minimum the principal one, as at Athens, Greece [KARAPIPERIS, 1945], and the interior desert type, with a weak to virtually no early morning minimum, as at Boise, Idaho [DAY, 1917]. There are other subtypes, but apparently rather local, as for example, that found at Athens during days with sea breeze, in which the diurnal march has triple maxima and minima [KARAPIPERIS, 1945].

In one and the same climate the diurnal march of vapor pressure varies from month to month and from one type of weather to another, through much, if not all, of the range between different climates. This is illustrated in Table 1.

Table 1--Types of vapor-pressure regimes for different ground and sky conditions

State of ground	State of sky	Vapor-pressure type
Moist	Cloudy	Oceanic
Moist or dry	Cloudy or partly cloudy	Continental
Moist	Clear	
Dry	Clear	Steppe or desert

In the present investigation the diurnal march of vapor pressure at Blue Hill (42° 13′ N, 71° 07′ W, altitude 635 ft), computed from the temperature and humidity records, has been studied for the months of January, April, July, and October of the five-year period 1940-1944, mainly with respect to the influence of the condition of the ground surface and cloudiness.

Diurnal march of vapor pressure--In Figure 1, the curves of the average diurnal march of vapor pressure are given for the months of January and July. (The times generally used in this paper are Eastern Standard or 75th meridian time. Local time averages 13 minutes earlier. The psychrometric observations are made about 13 minutes after the hour, so those times approximate mean local time.) It can be seen that, both in winter and summer, the diurnal marches are essentially of the oceanic type, almost parallel to the corresponding diurnal marches of air temperature. Nevertheless, at 13h a slight secondary minimum occurs in both months. As expected, the diurnal range in January (0.23 mm) is much less than in July (1.11 mm), when daytime mass exchange is large.

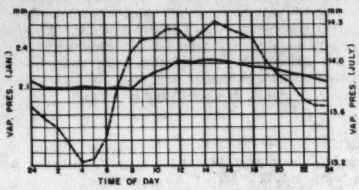


Fig. 1--Diurnal march of vapor pressure at Blue Hill, 1940-1944; January solid line, July dashed line

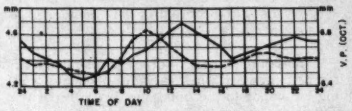


Fig. 2--Diurnal march of vapor pressure at Blue Hill, 1940-1944; April solid line, October dashed line

The diurnal march is markedly different in spring and fall, as shown by Figure 2. Although there are main and secondary maxima and minima in each curve roughly like the continental type, the hours at which the maxima occur differ from those of this type. Thus, while the main minima occur on the same hours as the minima of temperature in both months, the main maximum of April occurs at about 13h and that of October at 10h instead of in the evening. The secondary minima and maxima occur in the afternoon and evening hours, respectively, in both months. The diurnal range in April (0.43 mm) is somewhat greater than in October (0.36 mm).

Computation of average monthly vapor pressure--Using the above monthly curves of the diurnal march of vapor pressure, the difference between the mean daily values obtained from the three eye observations (7h, 13h, 19h) and the means of 24 hours was computed. It was found that the average from the three direct observations differs from the corresponding 24-hour average values as follows.

If $\overline{V}$ = the true mean vapor pressure, then

January $\overline{V} = (V_7 + V_{13} + V_{19})/3 - 0.03$ mm Hg

April $\overline{V} = (V_7 + V_{13} + V_{19})/3 - 0.04$ mm Hg

July $\overline{V} = (V_7 + V_{13} + V_{19})/3 - 0.11$ mm Hg

October $\overline{V} = (V_7 + V_{13} + V_{19})/3 + 0.01$ mm Hg

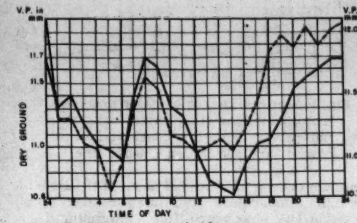


Fig. 3--Diurnal march of vapor pressure at Blue Hill during clear summer days with dry (solid line) and moist (dashed line) ground

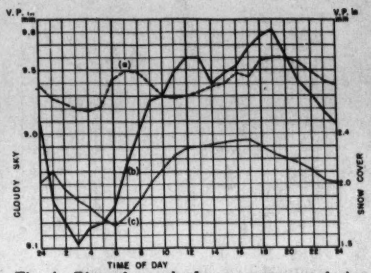


Fig. 4--Diurnal march of vapor pressure during (a) days cloudy at 14h in June at Potsdam [after MÖLLER, 1941]; (b) cloudy days without precipitation in summer at Pavlovsk [after GOODMAN, 1891]; and (c) days with snow cover at Pavlovsk [after RYKATSCHEW, 1908]

As the differences are insignificant, the formula (7h + 13h + 19h)/3 may be considered acceptable for providing accurate daily means.

Influence of ground condition and cloudiness on the diurnal march--For an examination of the influence of dry or moist ground on the diurnal march, clear days (0-30 pct mean daily cloudiness from 14 hourly observations 7 to 20h) in July and August were taken. The diurnal march was computed separately for days with dry and moist ground. The distinction between dry and moist ground is based on the international code for condition of the ground [INTERNATIONAL METEOROLOGICAL ORGANIZATION, 1948]: dry being Code No. 0; "Surface of ground dry (no appreciable amount of dust or loose sand)," for all three of the observations at 7h, 13h, and 19h; and, moist being Code No. 1, "Surface of ground moist," for all three. No cases of Code No. 2, "Surface of ground wet (standing water in small or large pools on surface)," were used.

The diurnal course during clear, dry summer days (see Fig. 3, solid line) has a double oscillation, with the main minimum at 15h, namely, at the time when turbulent mass-exchange is very strong. The secondary minimum is at 6h, about the time of the minimum temperature. The two maxima, which are almost equal, occur at 8h and 23-24h. Thus, the afternoon range (1.06 mm) is greater than the morning (0.79 mm), and the march is of the steppe type.

The diurnal march during clear summer days in July and August but with moist ground (see Fig. 3, dashed line), although also essentially a double oscillation, differs from that with dry ground and is roughly like the continental type. The main minimum comes at the same time as the minimum temperature, while the main maximum occurs about midnight. Because of the moist ground, which is cooler and is discharging vapor more rapidly, the addition of water vapor to the lower layers by evaporation tends to offset its removal by turbulent mass-exchange. Therefore, the main minimum does not occur during the afternoon. However, since the moist ground continues to supply water vapor, after convection weakens and ends, a significant increase is observed during the evening, and the main maximum occurs at midnight. This increase makes the afternoon range (1.02 mm) greater than the morning (0.89 mm) and the daily range (1.31 mm) greater than that with dry ground (1.06 mm).

Investigations into the diurnal march during cloudy days have not been previously made in the United States to our knowledge. Nevertheless, such studies at European stations show a continental type of march during June at Potsdam [MÖLLER, 1941] and during the summer days, when precipitation did not occur, at Pavlovsk [GOODMAN, 1891]. These are shown by curves (a) and (b) in Figure 4. For such a study at Blue Hill, summer days (July and August) were taken during which the mean daily cloudiness from 14 hourly observations (7 to 20h) was ≥ 80 pct, days with measurable rain being omitted. The condition of the ground, however, was either dry or moist. The computed values of vapor pressure are given by the full line in Figure 5, smoothed by the formula (a + 2b + c)/4. The diurnal fluctuation is like those of Potsdam and Pavlovsk, and is continental in type. Indeed, the Pavlovsk and Blue Hill curves are nearly identical. The main

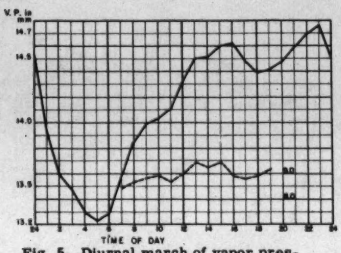


Fig. 5--Diurnal march of vapor pressure at Blue Hill during cloudy summer days (solid line); average cloudiness is shown by dashed line with scale at right

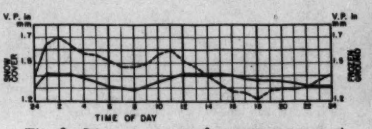


Fig. 6--Diurnal march of vapor pressure at Blue Hill during clear winter days with snow cover (solid line), and surface of ground bare and frozen (dashed line)

minimum occurs at Blue Hill about at the time of minimum temperature, while the secondary is observed at 18h, near which time a minimum of cloudiness is observed, as shown in the dashed curve of Figure 5. Therefore, it seems that this secondary minimum might not occur if the sky were completely covered by clouds. A special examination of overcast days revealed that the secondary minimum was, indeed, absent. The relatively great range in Figure 5 may be attributed to the higher average value of vapor pressure, to the usually moist ground, to a possible trace of rain (usually in the afternoon), and to the fact that most cloudy days are associated with the importation of warmer, moister air which is more likely to reach lower levels at midday or early afternoon (since in many cases a shallow layer of cold, dry air will persist at the surface during the night and morning).

A study of the march of vapor pressure on days with snow cover was made at Pavlovsk [RYKATSCHEW, 1908], where an oceanic type was found (see Fig. 4(c)). Though Rykatschew apparently included both clear and cloudy days, at Blue Hill only clear days with snow cover were studied. The curve for January is given in Figure 6 (solid line). In this case, as expected, the oceanic type prevails as at Pavlovsk owing to the continuously available vapor and the usually much-reduced turbulent mass-exchange over a cold surface, especially when the surface is somewhat smoothed by a snow cover. The range (0.14 mm) at Blue Hill is, naturally, smaller than the average (all days) range in January (0.23 mm).

Finally, the dashed curve of Figure 6 gives the diurnal march during those clear days of December with the "Surface of ground bare and frozen" (Code No. 3) [INTERNATIONAL METEOROLOGICAL ORGANIZATION, 1948], at least at 7h, 13h, and 19h. The fluctuation is roughly of the steppe type, with a nocturnal main maximum and an early evening main minimum (18h). This main minimum may be due to the cumulative effect of daytime turbulent mass-exchange above a somewhat heated, even though still frozen, ground. Air drainage and consequent descent of free air on the summit of Blue Hill in the evening may also be a factor.

Conclusion--The average diurnal march of vapor pressure at Blue Hill is essentially of the oceanic type in January and July, and roughly of the continental type in April and October. On clear summer days there is a double oscillation, which is of the steppe type when the ground is dry and of continental when it is moist. During cloudy summer days the fluctuation is usually continental in type at Blue Hill as well as at Potsdam and Pavlovsk. At Blue Hill the afternoon minimum tends to be weak, and is absent on overcast days.

At Pavlovsk as well as at Blue Hill a snow cover eliminates the afternoon minimum, so the march is of the oceanic type.

During clear days with the surface of the ground bare and frozen, the march is of the steppe type at Blue Hill.

Thus, the diurnal march of vapor pressure is mainly controlled by the availability of water at the surface and by the degree of turbulent mass-exchange.

Acknowledgments--Thanks are due C. F. Brooks and V. Conrad for their guidance and advice during the preparation of this paper at Blue Hill Meteorological Observatory.

References

CONRAD, V., Die klimatologischen Elemente und ihre Abhängigkeit von terrestrischen Einflüssen, Köppen-Geiger, Hb. Klimat., Berlin, v. 1, pt. B, pp. 376-378, 1936.

DAY, P. C., Relative humidities and vapor pressures over the United States, including a discussion of data from recording hair hygrometers, Mon. Wea. Rev., Sup. no. 6, 1917.

GOODMAN, K., Über den taglichen Gang der Temperatur und Feuchtigkeit in Pawlowsk an heiteren und trüben Tagen, Repertorium für Met., St. Petersburgh, v. 14, no. 8, pp. 77-107, 1891.

INTERNATIONAL METEOROLOGICAL ORGANIZATION, Conf. of Dir. Wash., Sept. 22-Oct. 11, 1947, List of Resolutions, pp. 116-117, Washington, D. C., 1948.

KARAPIPERIS, PH., Contribution to the study of the diurnal march of vapor pressure at Athens, Athens, Greece, 1945 (mimeographed, in Greek).

MÖLLER, F., Die Abhängigkeit des Dampfdrucktagesganges von Bewölkung und Windrichtung, Met. Zs., v. 58, pp. 252-253, 1941.

RYKATSCHEW, M., Über den Einfluss der Unterlage auf den taglichen Gang der absoluten Feuchtigkeit, Met. Zs., v. 25, pp. 501-510, 1908.

National Observatory of Athens,
Athens, Greece, and
Blue Hill Meteorological Observatory,
Harvard University,
Milton, Massachusetts

(Communicated manuscript received November 16, 1950, and, as revised, March 22, 1951; open for formal discussion until January 1, 1952.)

SURFACE OZONE AT COLLEGE, ALASKA

W. S. Wilson

Abstract--Indirect oxidation of sodium arsenite is used as an agent for the determination of daily average values of the concentration of ozone in the atmosphere near the surface. Such values obtained at College, Alaska, for the first three months of 1950 are given. These show large variations from day to day, the maxima often rising to many times the minima. Except for a few unusually high values which are apparently associated with special conditions in the Arctic atmosphere, the concentrations increase with increasing altitude of the Sun. As as rule, they are less uniform and higher than those reported from stations in lower latitudes.

Introduction--As a part of the program on the state of the atmosphere in the Arctic at the Geophysical Institute of the University of Alaska at College, Alaska (near Fairbanks), latitude 65° N, longitude 148° W, determinations of the daily average values of the concentration of ozone near the Earth's surface are being made by chemical means. In this preliminary paper are given the general details of the chosen method as well as a review of the results of measurements during the first quarter of 1950.

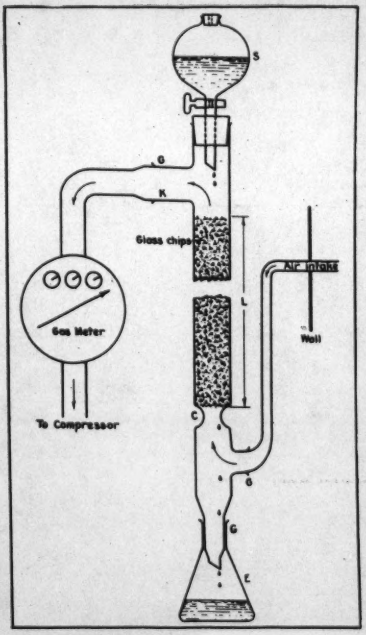


Fig. 1--Diagram of absorption column

Method--Any method for the chemical determination of the concentration of ozone near the surface must be very sensitive. Although this problem has not been satisfactorily solved, several methods have been proposed and used. Among these are (a) the oxidation of potassium iodide (oxidation of the iodide to iodine and subsequent titration of the released iodine by sodium thiosulfate [REGENER, 1949; JULIARD and SILBERSCHATZ, 1928]; (b) the oxidation of potassium iodide in the presence of sodium thiosulfate and subsequent titration; (c) the oxidation of potassium iodide in the presence of sodium arsenite and titration of excess arsenite with iodine [DAUVILLIER, 1934]; and (d) the oxidation of organic compounds such as tetrabase, fluorescein [BENOIST, 1919], or dihydroacridine.

Method (a) is being extensively applied by REGENER [1949], who hopes to develop a self-recording micromethod for the determination of ozone. The use of organic substances may have the advantage that one can follow the action of ozone either by changes in color or by analyzing the absorption spectrum. DAUVILLIER [1934] used method (c) in an extensive series of measurements at Scoresby Sund during the Polar Year.

The chemical reaction in Dauvillier's method is the oxidation by ozone of the iodide to iodine followed by the immediate oxidation of the sodium arsenite by the iodine to sodium arsenate. The simultaneous use of these two reagents is reported to be more specific and satisfactory than either alone. If kept away from heat and light, the solutions involved are reasonably stable. In applying this method, as well as any other, one must be sure that the ozone is completely absorbed. Too, because of low con-

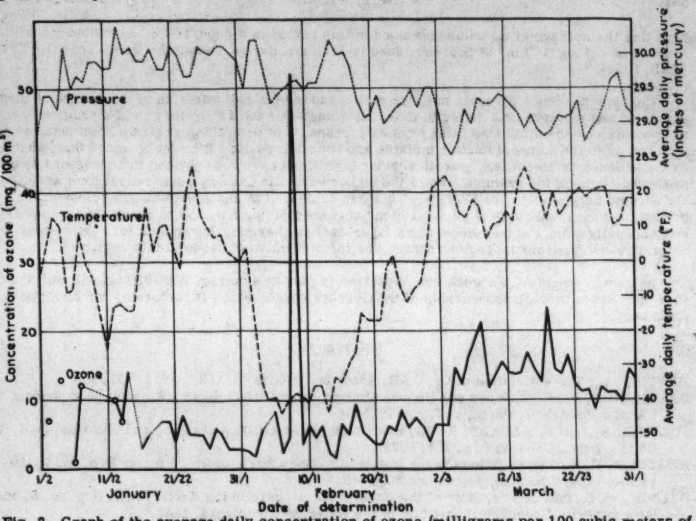


Fig. 2--Graph of the average daily concentration of ozone (milligrams per 100 cubic meters of dry air, STP), the average daily temperature (°F), and the average daily pressure (inches of mercury) for the first quarter of 1950

centrations of ozone, large volumes of air must be brought into contact with the absorbing liquid. This is accomplished in this series of measurements by using an apparatus similar to that of DAUVILLIER [1934] which provides for the continuous circulation of air. A sketch of the equipment is shown in Figure 1. Air from the outside is circulated by a compressor upward through the absorbing column of chipped pyrex glass and into a commercial gas meter. On cold days the incoming air is warmed by passage along a steam pipe. The absorption tube is three cm in diameter and is filled with pyrex glass chips for a length of one meter. The absorbing liquid (about 0.001 N in sodium arsenite, 0.001 N in potassium iodide, and 0.01 N in sodium bicarbonate) drips slowly over these chips at a rate of 500-600 cc in 12 hours. The same liquid is recirculated when used for 24-hour runs. Complete absorption is assured by regulating the flow of air to 12-15 m^3/day, about one-half of Dauvillier's rate. As Dauvillier remarked, it is necessary that the water used be uniform, that is, either very pure or having the same zero titration. The latter approach was used. Thus the values for ozone content obtained depended on the small difference between the titration value of an exposed solution and that of an unexposed solution. Samples of the absorbing liquid are made by adding 25.00 cc of 0.03 N sodium arsenite to 750 cc of the controlled water. The titrations were made using 0.02 N standard iodine in potassium iodide with sodium bicarbonate as a buffer. At the end of a run the column was carefully washed with 500 cc of water. The author believes that there are inherent weaknesses in working with large quantities for a small difference, though he observes that the method has given reasonable values in all but two instances. Too, it might be that the values obtained give a good picture of day-to-day changes but may be of little use in deducing absolute values.

Results--The daily values of the concentration of ozone in mg/100 m^3 for the first quarter of the present year, together with the average daily temperatures and pressures, are shown in Figure 2. Although the data show no spectacular correlation with any one factor, some trends may be observed among the various factors, for example, in several instances the value of ozone rises just before an increase in temperature. The general rise of ozone with the advance of the season seems to correlate with the rise in temperatures but probably only reflects the increase in total ozone due to the increasing altitude of the Sun. A direct correlation of these daily averages with pressure and wind direction is not significant. The ozone values, however, are much more irregular and average much higher than those mentioned by various authors for lower latitudes.

Note that the average of all values obtained in this period is 6.9 mg/100 m^3 as compared with an average of 8.3 mg/100 m^3 at Scoresby Sund in northern Europe during the Polar Year [DAUVILLIER, 1934].

Conclusion--Since the main purpose of this paper is to call attention to the method of measurement and to serve as a notice to those interested that the Laboratory is in a position to make such studies by chemical (and later physical) means, it is desirable to refrain from detailed conjectures as to the cause of certain isolated and unusual results. It might be added that, whether by coincidence or otherwise, special weather conditions have been noticed to correspond to unusual ozone values, for example, two of the higher values in January occurred on days when the air seemed very stable over College. This was evidenced by the smoke hanging close to the ground. The unusual value of 52 mg/100 m^3 occurred during a period in which the atmosphere was unusually calm and the temperature lapse-rate isothermal. It remains for future study to determine the fundamental factors controlling the movement of ozone in this region.

Acknowledgment--This work was supported in part by Contract W28-099 ac-445 with the U. S. Air Force through sponsorship of the Geophysical Research Directorate, Air Materiel Command.

References

BENOIST, L., The estimation of 0_3, C.-R. Acad. Sci., Paris, v. 168, p. 612, 1919.

DAUVILLIER, A., Recherches sur l'ozone atmospherique effectuées au Scorsby Sund pendant l'Année Polaire, J. Phys., v. 5, p. 558, 1934.

JULIARD, A., and S. SILBERSCHATZ, Iodometric determination of ozone and chlorine, Bull. Soc. Chim., Belg., Gand, v. 6, p. 204, 1928.

REGENER, V. H., Investigations in the physics of atmospheric ozone, Interim Rep. no. 7, University of New Mexico, September 30, 1949.

WILSON, W. S., and Others, State of the Earth's atmosphere in the Arctic, Res. Rep. no. 5, and later reports, Geophysical Institute of the University of Alaska, 1949.

Geophysical Institute,
University of Alaska,
College, Alaska

(Manuscript received April 3, 1950, and, as revised, April 23, 1951; presented at the Thirty-First Annual Meeting, Washington, D. C., May 1, 1950; open for formal discussion until January 1, 1952.)

Transactions, American Geophysical Union Volume 32, Number 4 August 1951

THE REPRESENTATION OF THE MAIN GEOMAGNETIC FIELD AND OF ITS SECULAR VARIATION BY MEANS OF TWO ECCENTRIC DIPOLES

Hans G. Macht

Abstract--On the basis of certain analytical aspects of geomagnetic potential theory, there is developed a physical model of the main geomagnetic field, consisting of two eccentric dipoles. This model, accounting exactly for the whole second-order potential portion, represents a generally improved approximation to the observed (terrestrial) surface field. The systematic displacements which both its dipoles have undergone since 1829 also suggest the existence of a superior "planetary component" in geomagnetic secular variation, expressed by an apparent periodicity of about 500 years. Considered in relation to relevant investigations by Bullard, Elsasser, Vestine, and others, the model gives rise to some hypothetical conclusions as to the nature and origin of the Earth's interior magnetic field. Despite its mainly analytical foundation, the model provides a material basis for the exact definition and computation of an improved "normal (planetary) geomagnetic field." Finally, the possibility of a rough prediction of this "normal field" for future epochs is considered.

Introduction--The abstract conception of the magnetic dipole has proved a suitable means for the physical representation of the main geomagnetic field as well as of its anomalies. The well-known central dipole, replacing the Earth's moment, $\vec{M}$, accounts for only the first-order potential constituents of that field. It is not possible to represent by this simplest physical model more detailed features (geomagnetic anomalies), corresponding to second- and higher-order spherical harmonic terms in the expansion of the magnetic potential. An eccentric dipole of equal strength, $\vec{M}$, shifted to the Earth's magnetic center C, does provide a generally better fit of the observed (terrestrial) surface field, as BARTELS [1936] has shown in an important paper. Such a dipole accounts for the major part (about 85 pct) of the terrestrial second-order potential portion. Yet there remain considerable regional anomalies which cannot be interpreted even by this improved model.

An interesting representation of the residual (observed minus eccentric dipole) field has been given by McNISH [1940]. Fourteen radial dipoles of suitable moment are placed eccentrically at the common depth R/2, R being the Earth's radius; each dipole corresponds to a large regional anomaly of the surface field. Though furnishing a good approximation to the terrestrial anomaly field, such a model consisting of many dipoles seems rather complicated. A representation of the characteristic features of the main geomagnetic field, including certain world-wide or "planetary" anomalies, by a system of as few dipoles as possible should be more appropriate to actual physical conditions relating to that field.

The next step following upon the assumption of one eccentric dipole would be, then, to construct a suitable model of two dipoles of this kind. A generally improved approximation to the actual surface field is indeed obtained by this model. Furthermore, an important constituent of geomagnetic secular variation is accounted for by the systematic displacement with time of those two dipoles.

Theoretical foundations--The most convenient basis upon which this model may be established is the well-known separation of $\vec{M}$ into a "polar" component $\vec{M}_p$, parallel to the Earth's axis of rotation, and an "equatorial" one $\vec{M}_q$, perpendicular to this axis. This analytical procedure rests physically on the conception that the overwhelming part ($\vec{M}_p$) of $\vec{M}$ is due in some way to the Earth's axial rotation, while, in order to allow for the actual inclination of the geomagnetic axis of about 11°.4 from the axis of rotation, the model must include a secondary, transverse geomagnetic dipole component $\vec{M}_q$, parallel to the equatorial plane. The relative strengths of the two components may be expressed by $|\vec{M}_p| \sim 5\,|\vec{M}_q|$.

From the analytical viewpoint, a decomposition of $\vec{M}$ into two separate, individual, partial fields, each corresponding to an equivalent (eccentric) dipole, is supported by certain considerations based upon spherical-harmonic potential expansion in geomagnetic coordinates. As already known, the sectorial second-order coefficient $c_2^{2\prime\prime}$ of this expansion, like the single dipole coefficient $c_1^{0\prime\prime} = m$, is invariant for parallel translations of the underlying geomagnetic coordinate system. Provisionally accepting fictitious point dipoles as equivalent sources of geomagnetism, the

condition $c_2^2'' = 0$ should result in the case of one eccentric dipole. Actually, in geomagnetic potential analysis, $c_2^2'' \neq 0$. This fact can be accounted for only by postulating two separate, eccentric dipoles whose vectorial resultant determines the polar axis, $\phi = 0°$, of the corresponding "geomagnetic" potential expansion [MACHT, 1948, 1950a].

The question whether any physical reality is likely to pertain to those equivalent, eccentric dipoles $\vec{M}_p$ and $\vec{M}_q$ together constituting $\vec{M}$ will be briefly reviewed later. As shown elsewhere [MACHT, 1949], it is possible to represent certain characteristic features of the main geomagnetic field by a rough model of two mutually perpendicular dipoles $\vec{M}_1$ and $\vec{M}_2$, the axes of which lie in the (geographic) zero meridian plane, $\lambda = 0°$. Thus, the striking elliptical shape of the V (potential), H (horizontal intensity), and I (inclination) isomagnetic contours in the polar regions can be accounted for, in principle, by such a model. Furthermore, an idealized pattern of the geomagnetic one-dipole residual field is obtained by subtracting from the surface field of this model that of the resultant central dipole $\vec{M} = \vec{M}_1 + \vec{M}_2$. (The two eccentric dipoles of this previous model, standing for the polar and transverse components of $\vec{M}$, were placed along the axis of rotation and in the equatorial plane, at the distances $e_1 = -R/10$ and $e_2 = +3R/10$, respectively, from the Earth's geometric center 0. In this particular case, $|\vec{M}_1| = 3|\vec{M}_2|$ was adopted, so that again $\vec{M}_1 + \vec{M}_2 = \vec{M}$).

That tentative model did not conform, however, with the true disposition in space of the Earth's magnetic axis. In order to allow for this as well as for the superior planetary geomagnetic anomalies, there is required an exact adjustment of the "actual" component dipoles $\vec{M}_p$ and $\vec{M}_q$ of $\vec{M}$ inside the Earth. This can be performed by means of the terrestrial first- and second-order magnetic potential coefficients, in such a way that all first- and second-order partial terms of the potential expansion are completely fitted by the final model.

As regards the three first-order (dipole) coefficients, the following relations hold

$$a_1^0 = c_1^0 = M_p/R^3 \qquad c_1^1 = M_q/R^3$$

where

$$(c_1^1)^2 = (a_1^1)^2 + (b_1^1)^2$$

Further

$$m = M/R^3 \qquad \text{where } m^2 = (c_1^0)^2 + (c_1^1)^2$$

Inserting the empirical values for epoch 1945.0, as given in Table 1 [VESTINE and Others, 1947], we have $m = -311.9 \times 10^2\gamma$.

In the aforementioned paper by Bartels, formulas are published [p. 249] for the second- and third-order coefficients $a_n^{m\prime}$, $b_n^{m\prime}$, of the magnetic field of an eccentric dipole, the rectangular (cartesian) components of which are $M_x = a_1^0 R^3$, $M_y = a_1^1 R^3$, $M_z = b_1^1 R^3$. Denoting the position

Table 1.--First- and second-order potential coefficients of the Earth's magnetic field
(in units of $10^2\gamma = 10^{-3}\Gamma$)

No.	Author	Epoch	a_1^0	a_1^1	b_1^1	c_1^{1*}	a_2^0	a_2^1	b_2^1	a_2^2	b_2^2
1	Erman-Petersen	1829	-320.1	-28.4	+60.1	66.4	- 0.8	+25.7	- 0.4	- 1.4	+14.6
2	Gauss	1835	-323.5	-31.1	+62.5	69.0	+ 5.1	+29.2	+ 1.2	- 0.2	+15.7
3	Adams	1845	-321.9	-27.8	+57.8	64.1	+ 0.9	+28.4	- 1.0	+ 0.4	+13.5
4	Adams	1880	-316.8	-24.3	+60.3	65.0	- 4.9	+29.7	- 7.5	+ 6.1	+14.9
5	Schmidt	1885 I	-316.8	-22.2	+59.5	63.5	- 5.0	+27.8	- 7.1	+ 6.5	+14.9
6	Fritsche	1885 II	-316.4	-24.1	+59.1	63.8	- 3.5	+28.6	- 7.5	+ 6.8	+14.2
7	Dyson/Furner	1922 I	-309.5	-22.6	+59.2	63.3	- 8.9	+29.9	-12.4	+14.4	+ 8.4
8	Bartels	1922 II	-309.0	-22.7	+58.6	63.0	- 6.7	+29.2	-12.2	+14.3	+11.3
9	Vestine	1945	-305.7	-21.1	+58.1	61.9	-12.7	+29.6	-16.6	+16.4	+ 5.4

$^* c_1^1 = +[(a_1^1)^2 + (b_1^1)^2]^{1/2}$.

C(x,y,z) of such a dipole by the dimensionless coordinates $\xi = x/R$, $\eta = y/R$, $\zeta = z/R$, with $|x|<R$, $|y|<R$, and $|z|>R$, the second-order coefficients of its magnetic field with respect to the coordinate system centered in 0 are

$$\left.\begin{aligned} a_2^{0\prime} &= 2\,a_1^0\,\xi - a_1^1\,\eta - b_1^1\,\zeta \\ a_2^{1\prime} &= (a_1^1\,\xi + a_1^0\,\eta)\sqrt{3} & b_2^{1\prime} &= (b_1^1\,\xi + a_1^0\,\zeta)\sqrt{3} \\ a_2^{2\prime} &= (a_1^1\,\eta - b_1^1\,\zeta)\sqrt{3} & b_2^{2\prime} &= (b_1^1\,\eta + a_1^1\,\zeta)\sqrt{3} \end{aligned}\right\} \quad \ldots\ldots\ldots (1)$$

(In Bartels' paper the term $a_1^0\eta$ in the formula for $b_2^{1\prime}$ should read $a_1^0\zeta$). Formulas (1) consist of factors each belonging to scalar potential terms. Hence they are purely additive, and apply also in the case of two or more eccentric dipoles.

Computation and discussion of the model--The mathematical problem now is to determine from (1) the coordinates ξ_p, η_p, ζ_p, and ξ_q, η_q, ζ_q, of $\vec{M}_p$ and $\vec{M}_q$, respectively, by inserting for $a_2^{m\prime}$, $b_2^{m\prime}$ the empirical values of the magnetic coefficients a_2^m, b_2^m for the Earth, epoch 1945.0 (Table 1). Disposing of only five second-order terms for six coordinates to be determined, a unique solution does not seem possible. This difficulty may be overcome by adopting a fixed value for one of those six coordinates. In this regard, the assumption $\xi_q = 0$ would represent analytically the simplest as well as physically the most reasonable condition; the transverse $\vec{M}_q$ dipole is presumed to lie in the equatorial plane. Its direction is such that if translated to 0 it would point to the meridian that contains the south end of the Earth's magnetic axis. Considering further that in (1) all the dimensionless quantities ξ, η, and ζ associated with a_1^0 refer to $\vec{M}_p$, and those associated with a_1^1 and b_1^1 to $\vec{M}_q$, formulas (1') to compute the positions of both eccentric dipoles result

$$\left.\begin{aligned} a_2^0 &= 2\,a_1^0\,\xi_p - a_1^1\,\eta_q - b_1^1\,\zeta_q \\ a_2^1 &= a_1^0\,\eta_p\sqrt{3} & b_2^1 &= a_1^0\,\zeta_p\sqrt{3} \\ a_2^2 &= (a_1^1\,\eta_q - b_1^1\,\zeta_q)\sqrt{3} & b_2^2 &= (b_1^1\,\eta_q + a_1^1\,\zeta_q)\sqrt{3} \end{aligned}\right\} \quad \ldots\ldots\ldots (1')$$

The two last formulas of (1') yield the position of $\vec{M}_q$ in the equatorial plane, namely

$$\left.\begin{aligned} \eta_q &= (a_1^1 a_2^2 + b_1^1 b_2^2)/(c_1^1)^2\sqrt{3} \\ \zeta_q &= (a_1^1 b_2^2 - a_2^2 b_1^1)/(c_1^1)^2\sqrt{3} \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots (2)$$

Then the position of $\vec{M}_p$ immediately results from (1') and (2), as follows

$$\left.\begin{aligned} \xi_p &= (a_2^0 + a_1^1\,\eta_q + b_1^1\,\zeta_q)/(2\,a_1^0) \\ \eta_p &= a_2^1/(a_1^0\sqrt{3}), & \zeta_p &= b_2^1/(a_1^0\sqrt{3}) \end{aligned}\right\} \quad \ldots\ldots\ldots (3)$$

Inserting values of the first- and second-order coefficients, epoch 1945.0 (Table 1), the final coordinates of $\vec{M}_p$ and $\vec{M}_q$, expressed in units of R, are

$\vec{M}_p$: $\xi_p = +0.036$ $\quad \eta_p = -0.056$ $\quad \zeta_p = +0.0314$

$\vec{M}_q$: $\xi_q = 0$ $\quad \eta_q = -0.065$ $\quad \zeta_q = -0.162$

The transverse $\vec{M}_q$ dipole is situated 1031 km from 0, the radius vector $0 \rightarrow \vec{M}_q$ designating the longitude $\lambda_q = 268°$ E. (The positive or magnetically north extension of the $\vec{M}_q$ axis makes an angle of 110°, in the equatorial plane, with the zero meridian plane, $\lambda = 0°$.) Thus, a relatively large eccentric position, displaced nearly R/6 from 0, must be adopted for this minor dipole component of $\vec{M}$.

Another important result exhibited by (3) is the asymmetric position of the polar $\vec{M}_p$ dipole

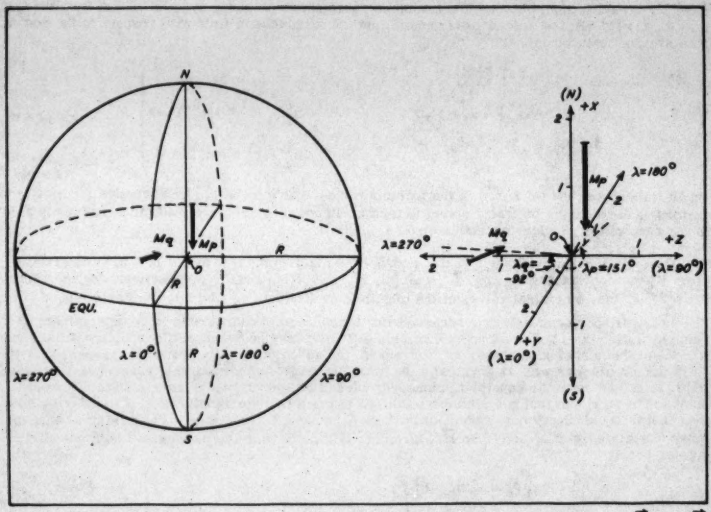


Fig. 1--Disposition within the Earth of two mutually perpendicular eccentric dipoles, $\vec{M}_p$ and $\vec{M}_q$, which together represent the main geomagnetic field, epoch 1945.0 (true sites of dipoles indicated by the arrowheads); on the right, enlarged central part of left-hand sketch to illustrate the positions of $\vec{M}_p$ and $\vec{M}_q$ with respect to Earth's center 0 (unit of length, 1000 km)

component, about 408 km away from the Earth's axis in the meridian half-plane $\lambda_p = 151°$ E. Analytically, this fact accounts for the still considerable terrestrial second-order coefficients a_2^1 and b_2^1. Practically it allows, in the main, for the well-known planetary asymmetry of H around the Earth's equatorial belt. Further, $\vec{M}_p$ is not situated in the equatorial plane but 228 km north of it. The latter fact is due to a second planetary asymmetry of the geomagnetic field, namely, a slightly stronger mean (equivalent) magnetization of the whole northern hemisphere as compared with the southern one [MACHT, 1950a].

In this way, an exact adjustment of the two eccentric dipoles $\vec{M}_p$ and $\vec{M}_q$ together composing $\vec{M}$ has been obtained. This essentially improved model of the main (interior) geomagnetic field wholly fits the terrestrial first-order (dipole) and second-order (quadrupole) magnetic potential constituents. The true disposition of both dipoles within the Earth is shown in perspective in Figure 1, the proper sites of $\vec{M}_p$ and $\vec{M}_q$ themselves being indicated by the heads of the arrows. Without entering into further analytical details, it may be of interest to mention here that about 24 pct of the whole geomagnetic third-order potential, V_3 is expressed by this new model, whereas one eccentric dipole ($\vec{M}$) in C expresses only 12 pct of it. The remaining 76 pct of V_3 thus should be the analytical manifestation of geomagnetic field constituents, predominately crustal anomalies, which cannot be accounted for by a physical model of even two eccentric dipoles.

The model here presented embodies three presupposed essential conditions, which are (1) $\vec{M}_p$ is parallel to the Earth's axis of rotation; (2) $\vec{M}_q \perp \vec{M}_p$; (3) $\xi_q = 0$. By dropping one or more of these conditions (for example, the last two) we could produce other arrangements of two eccentric dipoles compatible with the terrestrial first- and second-order potential coefficients, affording perhaps a better approximation to the whole third-order potential portion. However, such an arrangement would seem inadvisable for physical reasons as well as geometrical ones. First, it would be still more difficult to explain a component of $\vec{M}$ that is oblique to $\vec{M}_p$ and stronger than $\vec{M}_q$. Secondly, we should lose the advantage of a geometrically clear, intrinsic representation of of the secular change of our model, to be considered next.

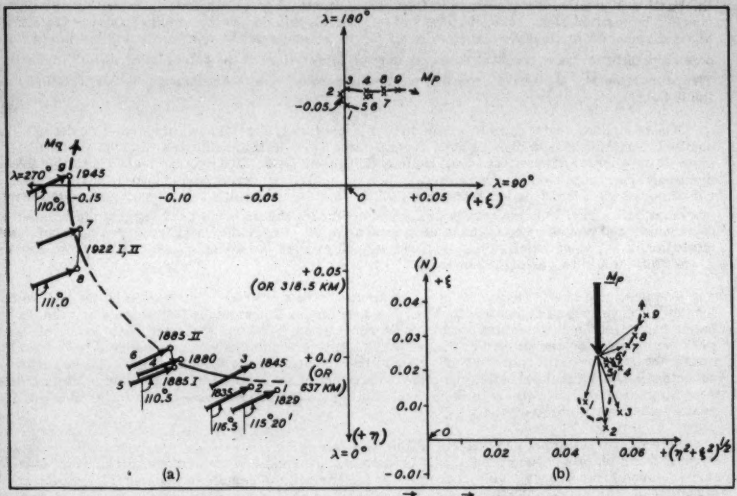


Fig. 2--Secular motion of the two eccentric dipoles $\vec{M}_p$ and $\vec{M}_q$ of the new geomagnetic model (Fig. 1); (a) viewed from a distant point above North Pole, displacement of $\vec{M}_q$ in the equatorial plane; simultaneous displacement of $\vec{M}_p$ (directed downward, perpendicular to that plane) with respect to Earth's axis (through 0); (b) viewed from a distant point in the equatorial plane at variable λ, displacements of $\vec{M}_p$ relative to Earth's axis as well as equatorial plane, at double the scale of Figure 2a; numbers of positions refer to epochs in Table 1; distances from 0 or x-axis, respectively, are shown in units of R.

The secular variation of the model--The particular advantage and special physical significance of the new model as a basic representation of the main geomagnetic field becomes evident when the displacement with time of both its dipoles or, simply, the SV (secular variation) of the model is taken into account. This can be done by means of available potential analyses for various epochs since 1829. Though representing somewhat inhomogeneous material, not strictly comparable from one epoch to another, these analyses permit a fairly accurate delineation of the general course of the SV evinced by the model during the past 120 years. For all epochs numbered in Table 1, the corresponding coordinates of $\vec{M}_p$ and $\vec{M}_q$ have been computed by (2) and (3). The final results are summarized in Figure 2, which gives an instructive picture of the apparent migration of both eccentric dipoles since the beginning of the nineteenth century.

Undoubtedly the most interesting feature exhibited in Figure 2 is the systematic westward motion of the transverse component of $\vec{M}$, as indicated by the curve interpolated between the positions of $\vec{M}_q$ for successive epochs. From 1829 until 1945, this eccentric dipole has moved along an approximately elliptical curve about 0 (or about a point a few hundred km from 0 towards the surface point $\phi = 0°, \lambda = 270°$). During that time the distance of $\vec{M}_q$ from 0 has increased from about 750 km to about 1030 km. It is of special interest to note further that the $\vec{M}_q$ magnetic axis remains nearly parallel to itself; the angle which it makes with the zero meridian half-plane varies only between 116°.5 and 110°.

The smaller displacements of the polar $\vec{M}_p$ dipole component of $\vec{M}$, occurring simultaneously with those of $\vec{M}_q$, are less pronounced and distinct. Nevertheless, these too reveal a systematic change in position of $\vec{M}_p$, parallel as well as perpendicular to the equatorial plane. Thus, the distance of $\vec{M}_p$ north of this plane has increased from only 19 km in 1835 to as much as 228 km in 1945, whereas the corresponding distance off the Earth's axis has increased from about 300 km to more than 400 km during the same time. At epoch 1945.0, the total distance of $\vec{M}_p$ from 0 was about 465 km. In spite of these considerable displacements of both dipoles, mainly of $\vec{M}_q$,

the Earth's magnetic axis (referred to the central dipole $\vec{M}$ in 0) has undergone relatively slight changes in position since 1829. In terms of our model, this constancy results from the facts that $\vec{M}_q$ is displaced practically parallel to itself (b_1^1/a_1^1 remains nearly constant), and that the two dipoles are of practically constant ratio, as may be inferred from the values of c_1^1 and a_1^0 in Table 1. The proportion $\vec{M}_p/\vec{M}_q \sim 5/1$ seems to hold quite generally, at least throughout the period of reliable data.

These striking features in SV of the model immediately disclose two important facts. (1) The continuous motion of both dipoles away from 0 since 1829 or 1835 indicates an obvious enhancement of the general asymmetry of the main geomagnetic field. The secular increase of the above-mentioned special planetary asymmetries finds its analytical expression chiefly in the systematic variations of the second-order coefficients a_2^0, a_2^1, and b_2^1 (see Table 1). (2) The rather uniform, systematic displacements especially of the equatorial $\vec{M}_q$ dipole since 1829 suggest the existence of a pronounced planetary constituent of geomagnetic SV of periodic nature. Supposing a continued migration of $\vec{M}_q$ along an elliptical orbit subsequent to 1945, as might be conjectured from Figure 2, one cycle would be performed in about 500 years.

The presence of a period in SV of approximately five centuries is supported by the well-known lengthy observations of D (declination) and I at London and other places in Europe since the sixteenth and seventeenth centuries. It has to be considered, however, that over large areas elsewhere such a period cannot be detected with reliability. These discrepancies should be due to strong irregular constituents of SV of regional nature, probably of crustal origin. These, being superimposed upon that periodic, planetary component of SV supposedly originating in the Earth's deep interior (core), are likely to disturb and obliterate the proper cycle of the latter of about 500 years over large terrestrial areas.

This interpretation of geomagnetic SV differs somewhat from the generally accepted view according to which this phenomenon should be mainly a regional one without any world-wide, planetary feature of importance. This conception is based upon the results of spherical harmonic analyses of the terrestrial SV field, which fail entirely to show the predominance of the first-order (dipole) terms that is such an outstanding feature of the main field itself. It has to be considered, however, that the planetary character of SV according to the hypothesis presented here is exhibited not by the relatively insignificant changes of the first-order coefficients, a_1^0, a_1^1, and b_1^1, but rather by the relatively large variations of the second-order coefficients, mainly of a_2^2 and b_2^2. These, giving rise to the described displacements of $\vec{M}_p$ and $\vec{M}_q$, seem thereby to confirm the existence of a superior, world-wide, periodic component of geomagnetic secular variation.

Physical interpretations.--Though founded on analytical considerations in the first place, the new model suggests some relevant physical interpretations bearing upon the nature, origin, and composition of the main geomagnetic field. The difference in magnitude between the secular displacements of the two eccentric dipoles $\vec{M}_p$ and $\vec{M}_q$ lends further support to the basic hypothesis of a complex interior field consisting mainly of two individual, separate parts. In particular, the conspicuous westward motion of the transverse $\vec{M}_q$ dipole seems to confirm the hypothetical assumption that the Earth's fluid core "lags" in its axial rotation behind the rigid crust [BULLARD, 1949; ELSASSER, 1950]. A secular retardation of the central core relative to the Earth's crust has been postulated by Elsasser and Bullard, as well as by SCHMIDT [1932] previously, in order to explain either certain periodic features of SV or the apparent westward migration of the so-called isoporic foci of the several geomagnetic elements. One may thus be inclined to ascribe the major part of the transverse $\vec{M}_q$ dipole field to complicated physical processes in the core such as convection currents and electromagnetic induction effects set up by the primary $\vec{M}_p$ dipole field.

As regards the polar $\vec{M}_p$ component, however, it seems dubious whether this could likewise be attributed in its major part to physical processes occurring in the Earth's core. According to VESTINE and Others [1947], planetary electric-current systems encircling the Earth's axis (or a line parallel to it) at depths probably between 1000 and 3000 km could be adopted as the main cause of this primary M_p field. This view might be supported by the relatively small secular movements of the $\vec{M}_p$ dipole as compared with those of $\vec{M}_q$, suggesting the $\vec{M}_p$ system to be physically associated with the solid part (mantle) of the Earth. Those movements of $\vec{M}_p$, parallel as well as perpendicular to the equatorial plane, might be interpreted as secondary modifications of the current-systems generating the $\vec{M}_p$ field. They could perhaps be caused by electromagnetic reactions of the minor $\vec{M}_q$ system partaking in the secular lag of the core.

The merely qualitative, hypothetical interpretations advanced here have to be regarded as but

tentative suggestions with reference to the aforementioned theoretical investigations by Bullard, Elsasser, Vestine, and others. Several important features of the model, in particular the striking fact that the $\vec{M}_q$ axis remains nearly parallel to itself during the large secular migrations of this dipole component, must still be left to future physical explanation.

Definition and prediction of an improved "normal field"--As pointed out above, the new model provides a better fit of the observed geomagnetic field than previous models using only one dipole. Therefore, leaving aside the question of physical reality, the proposal has been put forward [MACHT, 1950b] to define the terrestrial surface field of the two eccentric dipoles $\vec{M}_p$ and $\vec{M}_q$ as a "normal" or "fundamental geomagnetic field" (planetarisches Grundfeld) on a planetary basis. Assuming this combined $(\vec{M}_p + \vec{M}_q)$ field to originate deep within the Earth, its associated "residual" (observed minus fundamental) field should be likely to exhibit an improved correlation with the large tectonic structures of the Earth's crust. Such a particular residual field wholly eliminates the planetary, deep-seated geomagnetic first- and second-order field constituents, whereas the higher-order potential portions of mainly crustal origin are brought out more clearly and directly without being veiled by the second-order (quadrupole) components of the main field itself. As will be shown elsewhere, a fairly accurate representation of that fundamental field can already be obtained by spherical harmonic synthesis if its third-order potential portion is taken into account, along with the first- and second-order terms.

Finally, the possibility of a rough prediction of the fundamental field, at least for the forthcoming decades until about 2000, might be considered. This prediction could be performed by extrapolating the mean SV of the model, as represented by the migration of the constituent dipoles $\vec{M}_p$ and $\vec{M}_q$ along elliptical orbits during the past 120 years. A detailed computation of the true surface geomagnetic field for future epochs, however, seems impossible because of the quite irregular, non-periodic nature of the strong regional (crustal) SV constituents. Furthermore, the regular, or planetary, component of SV is also dependent upon the variations in strength of $\vec{M}_p$ and $\vec{M}_q$ themselves. The continued decrease of $|\vec{M}|$ or $|\vec{M}_p|$ and $|\vec{M}_q|$, respectively, which has been observed since 1829 (see Table 1), seems to have lessened during the last two or three decades [VESTINE and OTHERS, 1947]. A slow recovery of $|\vec{M}|$ which perhaps has reached a minimum at present might possibly occur in the coming decades of this century. The moment of both equivalent, eccentric dipoles $\vec{M}_p$ and $\vec{M}_q$ probably depends somewhat upon their mutual position within the Earth. A variation in the absolute strength of $\vec{M}$ with a period also of about 500 years might therefore be conjectured in accordance with the above presumed cycles of revolution of $\vec{M}_q$ as well as of $\vec{M}_p$.

Summary--In conclusion, it has to be emphasized again that the physical representation of the main geomagnetic field by two eccentric dipoles offers an improved approximation to the actual terrestrial surface field. Nothwithstanding its purely hypothetical and analytical foundations, this model furnishes a preliminary basis for a physically reasonable interpretation of several characteristic features of the main geomagnetic field as well as of its SV. Especially, the existence of a long-period, planetary component of geomagnetic SV seems to be established in principle by the systematic secular displacements of the two dipoles $\vec{M}_p$ and $\vec{M}_q$ together constituting the model. Thus, some support is given to the hypothesis of a complex geomagnetic interior field consisting mainly of two separate, individual parts: (1) The primary, or polar, $\vec{M}_p$ dipole field originating in the deeper solid layers of Earth (current-systems between 1000 and 3000 km); (2) the transverse, secondary, $\vec{M}_q$ dipole field in the core, probably induced by that major $\vec{M}_p$ field. Further, the model provides an exact basis for the definition of an improved, planetary normal or fundamental geomagnetic field. A rough prediction of the latter seems possible for some decades by extrapolating the general course of SV shown by the model since 1829.

It was not the purpose of this paper to elaborate detailed physical theories on the cause and origin of the main (interior) geomagnetic field. It is hoped, however, that the new model developed herein will stimulate further discussion and promote fundamental research in geomagnetism.

Acknowledgment--The present author is indebted to H. H. Howe of the National Bureau of Standards, Washington, D. C., for helpful criticisms and valuable suggestions relating to this investigation.

References

BARTELS, J., The eccentric dipole approximating the Earth's magnetic field, Terr. Mag., v. 41, pp. 225-250, 1936.

BULLARD, E. C., The magnetic field within the Earth, Proc. R. Soc., Ser. A, v. 197, no. 1051, pp. 433-453, 1949.

ELSASSER, W. M., The Earth's interior and geomagnetism (with further pertinent references), Rev. Mod. Phys., v. 22, pp. 1-35, 1950.

McNISH, A. G., Physical representations of the geomagnetic field, Trans. Amer. Geophys. Union, v. 21, pp. 287-291, 1940.

MACHT, H. G., Das "absolute Quadrupolmoment" - Eine magnetostatische Fundamentalgrösse und ihre geophysikalische Bedeutung, Zs. Naturforschg., v. 3a, pp. 189-195, 1948.

MACHT, H. G., Zur physikalischen Darstellung des magnetischen Restfeldes der Erde, Deutsche Hydrogr. Zs., v. 2, pp. 35-43, 1949.

MACHT, H. G., Die Potentialanteile 2. und höherer Ordnung des Erdmagnetfeldes - pt. 1, Gerlands Beitr. Geophysik, v. 62, no. 2, pp. 127-153, 1950a (pt. 2, in press; pt. 3 to appear in v. 63).

MACHT, H. G., Zur exakten Definition und Berechnung eines planetarischen erdmagnetischen Grundfeldes, presented at meeting of Deutsche Geophysikalische Gesellschaft, Hamburg, Oct. 24, 1950 (to be published later), 1950b.

SCHMIDT, A., Das Rätsel der erdmagnetischen Säkularvariation, Terr. Mag., v. 37, pp. 225-230, 1932.

VESTINE, E. H., L. LAPORTE, I. LANGE, and W. E. SCOTT, The geomagnetic field, its description and analysis, Carnegie Inst. Washington Pub. 580, 1947.

Beseler Allee 7,
Kiel, Germany

(Communicated manuscript received January 23, 1951, and, as revised, May 15, 1951; open for formal discussion until January 1, 1952.)

Transactions, American Geophysical Union Volume 32, Number 4 August 1951

SIX ADDITIONAL YEARS OF SPONTANEOUS INCREASE IN MAGNETIC MOMENT

By Patrick L. O'Dea and H. Herbert Howe

Abstract--The spontaneous increase in magnetic moment of magnet 31LC has been the subject of two previous reports. The present paper, in furnishing approximately six additional years of data, reveals that the rate of increase of magnetic moment is now approaching zero, indicating the near extinction of this magnet's remarkable quality. The total increase in moment has been nearly 1.5 pct. In contrast, a similar magnet, made in 1941 from the same type of steel, but not heat-treated at the same time, has shown a six per cent decrease in magnetic moment.

Background--Magnet 31LC is the so-called long magnet used with Coast and Geodetic Survey magnetometer 31. A hollow cylinder 10 cm in length and composed of 36 pct cobalt steel, this magnet was made in 1937 when the magnetometer was reconditioned. Since 1940, magnetometer 31 has been the standard absolute instrument at the Tucson Magnetic Observatory, where it has been used on an average of twice a week in observing horizontal intensity (H). As a regular check on the behavior of the magnet, the common logarithm of magnetic moment is obtained from each set of H computations, corrected to a temperature of 20°C, and tabulated (log M_{20}).

Previous papers--HOWE [1943] presented data showing that the magnetic moment of magnet 31LC had been increasing since 1939, contrary to the usual experience with permanent magnets, and that this increase occurred only during the summer.

With more data available, NELSON and CAMPBELL [1945] plotted the curve of log M_{20} over a five-year period and then eliminated the yearly rise, in an effort to get a clear picture of the

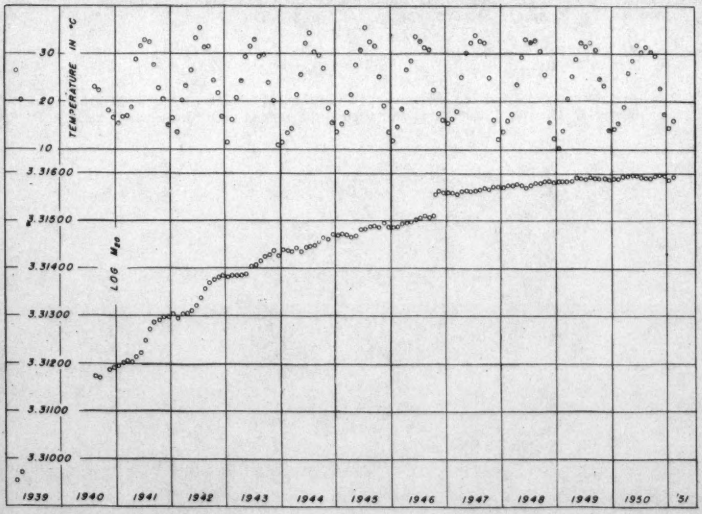


Fig. 1--Mean monthly values of log M_{20} and temperature for magnet 31LC

seasonal variation of moment. This turned out to be approximately a damped sine curve, leading the authors to predict that the magnetic moment would cease to increase after a few more years, about 1948.

The graph--Figure 1 is a digest of all determinations of the magnetic moment of magnet 31LC, the data since mid-1945 being published for the first time. Points forming the lower curve represent the monthly mean values of the logarithm of a magnetic moment, corrected to 20°C. Monthly mean values of temperatures observed during horizontal-intensity observations are also shown.

In October 1946, the long and short magnets of magnetometer 31 were accidentally allowed to come in contact with each other during a practice set of H observations. As a result, magnet 31LC showed an immediate sharp increase of magnetic moment, which appears on the graph as a discontinuity or jump. This incident makes it impossible to determine the accuracy of the prediction made by Nelson and Campbell, since the touching of the two magnets may or may not have affected the subsequent behavior of magnet 31LC. The pre-jump and post-jump October means were plotted separately.

A look at the log M_{20} curve after 1946 shows a slight positive slope which is flattening out as the rate of increase of magnetic moment approaches zero. The magnetic moment of 31LC has increased nearly 1.5 pct from 1939 to 1951.

By way of contrast, it may be noted that magnet 30L, which was manufactured from the same type of 36 pct cobalt steel as magnet 31LC, has shown a drop in magnetic moment from 1961 c.g.s. units in 1941 to 1837 c.g.s. units in early 1951, a decrease of 6.3 pct. However, the magnets were not heat-treated at the same time, and this process may have played an important part in determining the peculiar property of magnet 31LC.

References

HOWE, H. HERBERT, On spontaneous increase of magnetic moments, Trans. Amer. Geophys. Union, pp. 222-226, 1943.

NELSON, J. H., and J. B. CAMPBELL, Additional data on the spontaneous increase of magnetic moment, Trans. Amer. Geophys. Union, v. 26, pp. 379-380, 1945.

U. S. Coast and Geodetic Survey,
Washington 25, D. C.

(Manuscript received April 24, 1951; presented at the Thirty-Second Annual Meeting, Washington, D. C., May 1, 1951; open for formal discussion until November 1, 1951.)

Transactions, American Geophysical Union Volume 32, Number 4 August 1951

DIURNAL HEATING OF THE SURFACE OF THE GULF OF MEXICO IN THE SPRING OF 1942

Henry Stommel and Alfred H. Woodcock

(Contribution No. 553 of the Woods Hole Oceanographic Institution under contract with the Office of Naval Research)

Abstract--The diurnal temperature change of the surface layer in the Gulf of Mexico in the spring of 1942 seems to be qualitatively related to the computed net flux of heat at the surface and to the wind force, being greatest for sunny, calm days. A numerical analysis of the data is attempted: The eddy conductivity is computed by two methods, and the results are conflicting.

Introduction--The thermal structure of the surface water is the result of a complex interplay of many processes of heat transfer [GEIGER, 1950, p. 153]. Immediately at the sea surface the flux of heat occurs in many forms: by solar radiation, both direct and scattered; by infra-red radiation from the surface, and from the atmosphere to the sea; by conduction; and in a latent form by evaporation of surface water. The net flux of heat through the surface is the algebraic sum of all these various forms of heat flux.

Below a depth fixed arbitrarily at which solar radiation is imperceptible, the heat flux is entirely by eddy conductivity of heat. It is controlled by the temperature gradient and the coefficient of eddy thermometric conduction. The dependence of this coefficient on the thermal structure and field of mean motion is not clearly understood.

The water layer between the surface and this arbitrary depth heats or cools, depending upon whether or not the net surface flux of heat into the layer exceeds the flux out at the bottom.

The diurnal variation of solar radiation produces the most marked fluctuation in the net heat flux at the surface. This is reflected in a corresponding change in the temperature of the surface layer. If the loss of heat through the depth below which eddy conduction predominates is great, the diurnal variation of temperature will not be so pronounced. Variations in this flux will be associated with variations in the coefficient of eddy thermometric conductivity, and this in turn will, we suppose intuitively, depend upon the force of the wind.

In terms less susceptible to quantitative interpretation, but more pictorial, we may think of this problem in the following way: The surface accumulates heat if the net surface flux is downward and if the wind does not "mix the heat down" to lower layers.

During the two periods March 26-April 3 and April 13-27, 1942, the Atlantis drifted with the surface water in the Gulf of Mexico. An attempt was made to remain always in the same portion of the surface water by determining the drift of the ship by means of her motion relative to a free drag, and then sailing back to the computed position of the surface water once each day. One of the purposes of this cruise was to study the diurnal heating of the surface water. The central region of the Gulf of Mexico is particularly suited for this kind of study, because the currents are weak and advective effects presumably small. As a result, the net flux of heat is analyzed on the assumption that it is vertical. These data were obtained under the supervision of the second author. The purpose of this paper is to record and discuss this interesting series of observations.

Preparation of the data--The body of data consists of hourly bathythermograms, wet- and dry-bulb air temperatures, sea surface temperatures, wind force, and cloud cover on a scale of tenths.

The data are not, strictly speaking, a continuous series. For example, there is a break of about a week (April 4-12) during which the Atlantis was in port, and during the night of April 17-18 she sailed to the southeast to avoid a current into which she had drifted. Because of these breaks in the series it is natural to study the data in several distinct portions. We will study in particular the series from April 18-27, which represents a reasonably unbroken continuous series. The positions of the Atlantis during the entire drifting period were within the area of the Gulf of Mexico shown in Figure 1.

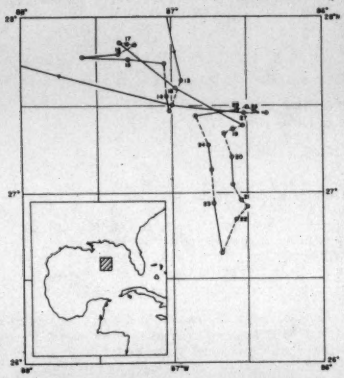


Fig. 1--The position of the Atlantis in the Gulf of Mexico during April 1942; the numbers next to the fixes indicate the day of the month; the shaded area in the inset map shows the location of the area

Figure 2 shows typical diurnal variations in the temperature of the surface water to a depth of 20 fm as well as the computed net heat flux and wind force at the surface. The purpose of this figure is to provide a rough qualitative picture of the phenomena.

Figure 3 shows the temperature variations at various depths for the selected period of April 18-27.

Computation of the surface heat flux--A column of water of one sq cm horizontal section is considered, extending from the surface down to a depth of 40 fm. The net flux of heat F (in whatever form) is taken as positive upward. At the surface this flux is composed of a number of terms.

$$F_o = Q_s + Q_b + Q_d \quad \ldots\ldots\ldots (1)$$

Q_s is the solar radiation flux, both direct and scattered, corrected for cloudiness according to the formula [SVERDRUP, JOHNSON, and FLEMING, 1942, p. 102]

$$Q_s = -Q_o (1 - 0.071C) \quad \ldots\ldots\ldots (2)$$

where C is the cloudiness on a scale of tenths, and Q_o is the incoming radiation with a clear sky; Q_b is the back radiation in the infra-red of the sea surface, given by the formula [SVERDRUP and others, 1942, p. 112]

$$Q_b = Q_o' (1 - 0.083C) \quad \ldots\ldots\ldots (3)$$

in which

$$Q_o' = sT^4 (0.56 - 0.08\sqrt{e}) \quad \ldots\ldots\ldots (4)$$

where e is the vapor pressure in millibars, T is the absolute temperature, and $s = 1.178 \times 10^{-7}$ cal/sq cm day (deg abs)4; and Q_d is the heat flux through the surface by direct heat conduction and by evaporation [MONTGOMERY, 1940].

$$Q_d = Q_e + Q_c \quad \ldots\ldots\ldots (5)$$

where

$$Q_c = h_c (\theta_s - \theta_d) \quad \ldots\ldots\ldots (6)$$

$$Q_e = h_e (e_s - e_d) \quad \ldots\ldots\ldots (7)$$

The coefficients h_c and h_e are functions of the wind force, but their values are only roughly known. Very approximate values are given in Table 1. θ_s and θ_d are Fahrenheit temperatures of the sea surface and air at deck level respectively; e_s is the saturation vapor pressure of water in millibars at the sea surface; and e_d is the vapor pressure at deck level.

The quantities Q_s, Q_b, Q_c, Q_e, have been computed according to the above formulas from the meteorological data.

The values of the surface heat flux determined by these formulas are undoubtedly very rough and subject to error, as pointed out by THORNTHWAITE and HOLZMAN [1942]. Unfortunately, even the probable error is unknown.

Qualitative description--In Figure 2 we have representative examples of the diurnal heating process. The computed net heat flux at the surface is plotted at the right of each diurnal series of temperature soundings.

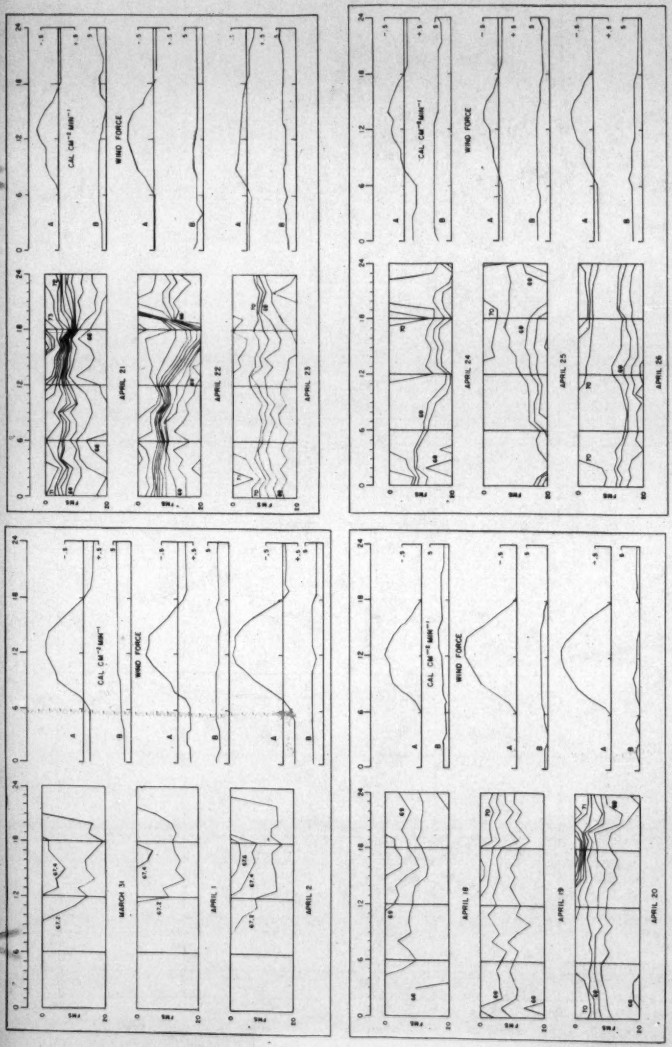


Fig. 2-- Selected cases of diurnal heating; the tithe-depth profiles drawn from the hourly bathythermograms are drawn on the left; the contour interval is not the same in all cases: 0.2°F for March 31, April 1 and 2, but 0.5°F for the other days shown; the computed net heat flux positive upward at the surface is shown plotted against time of day on the right in the curves labelled A; the observed wind force as a function of time in the curves labelled B

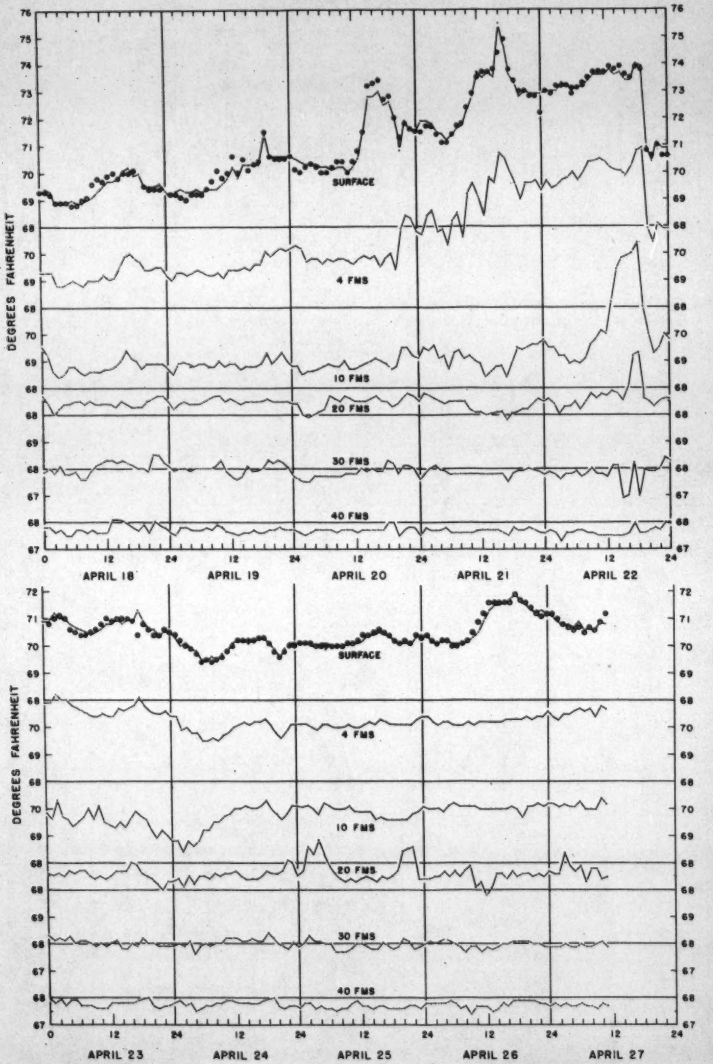


Fig. 3--Hourly temperatures at fixed depths as read from bathythermograms; a break in the series occurs at 19h 00m April 22 because of a shift in position of the ship; the small circles are the hourly surface bucket temperatures

Table 1--Sensible and latent heat transfer coefficients

Wind force, Beaufort	1	2	3	4	5	6
h_c, cal/sq cm hr deg F	0.10	0.20	0.30	0.41	0.53	0.66
h_e, cal/mb sq cm hr	0.29	0.58	1.00	1.75	3.00	4.60

The temperature soundings for March 31, April 1, and April 2 are shown. During the nights the water was perfectly homogeneous. There was considerable loss of heat during the night, but, on the whole, more heat was added to the water during a 24-hr period than was lost.

A good example of the progress of events may be found in the first series, that for March 31. The water is vertically homogeneous in the early morning, and is losing heat to the atmosphere, mostly in the form of latent heat of evaporation. The sun rises at 06h 00m (+5 zone). The flux of heat across the surface reverses sign by 07h 00m, and increases to a maximum at about 13h 00m. About 09h 00m the temperature of the surface water begins to increase and continues to do so until about 17h 00m, or about as long as the net surface flux is negative. The sea begins to lose heat through the surface at 18h 00m, and the water is homogeneous again by 21h 00m. The heat added during the day (07h 00m - 18h 00m) was about 360 cal/sq cm. Thus it is consistent to suppose that about 80 cal/sq cm must have been conducted to deeper layers by eddy transfer processes. This paragraph is not the place for quantitative discussion. It is good to realize, however, that the net heat flux at the surface is more than enough to produce the observed surface-layer heating.

The following two days are qualitatively similar. The morning of April 1 was cloudy, so that the surface heating was delayed. April 2 was a clear day. The net surface flux was greater, and the surface heating correspondingly greater.

During the three days, April 18, 19, and 20, the wind was progressively weaker, and the heat flux greater. The water was not homogeneous at night, nor was there any considerable loss of heat through the surface at night. The diurnal heating of the top three or four fathoms is clearly greatest for April 20, the day on which the surface heat flux is greatest and the wind least.

On April 21 the thermal gradients of the day before persist. On April 22, at 18h 00m, the Atlantis shifted position. It seems that a new water mass was entered by the end of April 22.

April 23 was a cloudy day with rising winds. The surface heating was small. The same is true of April 24 and 25. By the end of April 25 the wind fell, the sky cleared partly, and there was some rise in surface temperature late in the day.

This series of days represents a selected set of cases. The writers feel that they demonstrate, in a striking manner, the fact that clear days with light winds are the most favorable for the development of a thin, warm, surface layer (or, alternatively, of a strong thermal gradient at the surface). Cloudiness, or windiness, or both, are unfavorable to this development. It is a question whether much can be expected by subjecting them to a gross numerical analysis such as is attempted in the following paragraphs.

Method 1: If there is a depth $z = -h$ below which θ does not change with time, we can compute A at any depth z_1 by the equation

$$A_{z_1} = \left[\int_{-h}^{z_1} (\partial\theta/\partial t)dz\right]/[(\partial\theta/\partial z)_{z_1}] \quad \ldots\ldots\ldots\ldots\ldots\ldots (8)$$

Method 2: If at the surface $z = 0$ we know the net flux of heat F_0, we can use the surface as a reference level for computing A at $z = z_1$.

$$A_{z_1} = [F_0/C + \int_{z_1}^{0} (\partial\theta/\partial t)dz]/[(\partial\theta/\partial z)_{z_1}] \quad \ldots\ldots\ldots\ldots\ldots\ldots (9)$$

Method 3: If A is independent of depth, then

$$\partial\theta/\partial t = A\,\partial^2\theta/\partial z^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (10)$$

and A can be determined by direct evaluation of $\partial\theta/\partial t$ and $\partial^2\theta/\partial z^2$ from the data. The great weakness of this method is that it depends upon second differences, which in the present data are subject to great error.

Actual computations made by various methods--Method 1: Inspection of Figure 3 reveals that even at a depth of 40 fm there are fluctuations in the temperature as read from a bathythermogram with a standard deviation of about $\pm 0.1°F$. It is not possible to decide whether these are because of a lack of precision of the instrument or represent actual variations in the temperatures measured: short-period internal waves, turbulent fluctuations, or horizontal heterogeneities through which the ship drifted. Whatever they may mean, it is clear that they are of such a magnitude that if the heat content of a column is figured by integrating the measured temperature from the surface to a depth of 40 fm, it will be subject to fluctuations of such an order of magnitude as to obscure the diurnal variations in heat content. If we average the heat contents of several consecutive hours' soundings, then we reduce the range of fluctuation but in this way, too, obscure the diurnal variation.

Method 2: The computed surface flux is used as the known flux at the surface in terms of which we compute that at lower levels. The eddy conductivity is computed at the depth of four fathoms, using three-hour means to avoid the effect of short-period fluctuations due to local causes unrelated to the heat flux (such as internal waves).

If the values of A are plotted individually against wind force, they show a great scatter. It is not possible to decide whether this scatter is due to errors of the bathythermograph, actual inhomogeneities in the water, uncertainties in the computed surface heat flux, or real deviations of the eddy coefficient.

The means of the eddy coefficient for various ranges of the wind force are plotted against mean wind force in Figure 4. The number next to each plotted point represents the number of

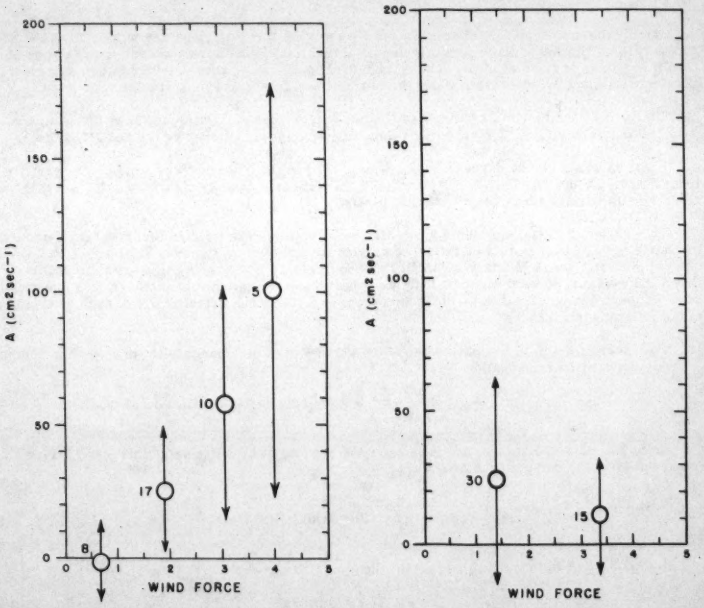


Fig. 4--Mean eddy coefficients as functions of wind force computed by Method 2; the arrows show the range of the mean deviation of individual values; the numbers indicate the number of individual determinations entering each mean

Fig. 5--Same as Figure 4, but computed by Method 3

individually computed eddy coefficients in the mean; the double arrows represent the mean deviation. Two extremely large eddy coefficients were omitted from the data used in Figure 4 on the ground that the ship was moving under power at the time. All eddy coefficients for times when the temperature gradient was less than 0.1°F per four fathoms were omitted from the compilation of the means for Figure 4, because the uncertainty introduced in the computation of the eddy coefficients is particularly great for small temperature gradients. The data were not selected in any other manner, however. The net result is that the eddy coefficient at four fathoms increases with increasing wind force. The result does not seem unreasonable, but cannot be regarded as proven because of the uncertainties involved. It might be the result, for example of a systematic error in the evaporation formula.

Method 3: Using the same three-hour means we computed the eddy conductivity A at a depth of six fathoms, for all the data of the period shown in Figure 3, with the exception of those during the night of April 22, when the ship shifted position. Cases of small $\partial^2\theta/\partial z^2$ were rejected on account of the great influence of error in such cases. The resulting values of A show a great scatter. They were gathered into two groups according to whether the wind force was greater or less than 2.5. The means and mean deviations of these two groups are plotted in Figure 5. They indicate a trend the opposite of that shown by Figure 4.

Method 2 would be the most reliable were the heat loss due to evaporation well known. Method 3 is weak on account of the immense errors entering through the second differences. A relation between the eddy conductivity and wind force such as shown in Figure 4 seems reasonable, but has not been demonstrated, and is contradicted by Figure 5.

Recommendations for further study--As a result of studying these data, several recommendations for future studies of this kind suggest themselves: (1) In addition to the serial bathythermograms it would be helpful to have continuous recordings of the temperature at a number of fixed depths. (2) A pyrheliometer would be a valuable addition to the instruments in order to measure the solar radiation directly rather than depend upon formulas involving estimates of cloudiness, and related factors. (3) Psychrometric and wind-velocity measurements should be made at two or more levels to permit use of a better evaporation formula, such as that of Thornthwaite and Holzman. (4) Because wind-speed measurements are so difficult from a ship, one wonders whether a large, nearly submerged buoy, with a mast for meteorological measurements, and a trailing cable for recording sea temperature at various depths, would not be the most satisfactory instrument for studies of this kind. It would be more stable than a ship, would remain in more nearly the same mass of water, and could be left unattended for a day or so.

References

GEIGER, R., The climate near the ground, Harvard Univ. Press, 1950.

MONTGOMERY, R. B., Observations of vertical humidity distribution above the ocean surface, and their relation to evaporation, Papers Phys. Ocean. Met., v. 7, no. 4, 30 pp., 1940.

SVERDRUP, H. U., M. W. JOHNSON, and R. H. FLEMING, The oceans; their physics, chemistry, and general biology, Prentice-Hall, Inc., 1087 pp., 1942.

THORNTHWAITE, C. W., and BENJAMIN HOLZMAN, Measurement of evaporation from land and water surfaces, U. S. Dept. Agriculture Tech. Bull. No. 817, 142 pp., 1942.

Woods Hole Oceanographic Institution,
Woods Hole, Massachusetts

(Communicated manuscript received January 16, 1951;
open for formal discussion until January 1, 1952.)

ACTIVITY OF PARICUTIN VOLCANO FROM JULY 1 TO DECEMBER 31, 1950

Carl Fries, Jr. and Celedonio Gutiérrez

(Publication authorized by the Director, United States Geological Survey)

The activity of Parícutin Volcano was under continuous daily observation during the second half of 1950. At such times when the junior author was away from the observatory at Cuezeño station, his assistant, Jesús Saldaña, maintained the detailed records and diagrams that serve as a basis for these six-month activity reports. During the second half of 1950 the senior author spent a total of 15 days at the observatory (July 6-9, August 30-September 2, October 22-24, and December 27-30). The junior author, aided by Saldaña, obtained the basic data used in compiling the eruptive diagrams (see Fig. 1-3) and in preparing the monthly summary of weather conditions, rainfall, and ashfall (see Table 1). They also mapped the monthly advance of the lava fronts (see Fig. 4) and noted significant events and changes that occurred during the period. The senior author prepared the remaining tables and figures and wrote the present report.

Eruptive activity--A detailed record of the eruptive activity for the second half of 1950 is given in the diagrams in Figures 1-3. A description of the lettered noise types used in these diagrams was included in the last Parícutin activity report published in these Transactions [FRIES and GUTIÉRREZ, 1951, Table 1, p. 216]. Eruptions from the crater were on the whole somewhat less strong than formerly, although short periods of intense activity continued to occur from time to time. A typical period of fairly quiet eruptions that were heavily laden with ash and bombs is illustrated by the photographs in Figures 5 and 6, taken from the northwest rim of the crater on December 29. Such activity produces an eruptive column from which streamers of ash descend over the terrain beneath.

The eruptive column reached a height of 3000 m above the crater on one day each in July, September, and November, although it averaged little more than 1500 m in height during the six-month period. Electric discharges were observed in the column on four days in July, five days in September, six days in October, two days in November, and two days in December. Brief intervals of two to four minutes of complete quiescence, followed by tremendous explosions that blew out enormous tonnages of pyroclastic material, occurred on two or three days each in October and December. Such explosions were always accompanied by local Earth tremors. Less violent explosions were observed on one to four days of every month. A strong regional earthquake, whose epicenter was in the State of Oaxaca some 600 km to the southeast, shook the area on December 16 without causing any visible change in eruptive or lava activity on that or the following day.

The strongest eruptions hurled rocks to a height of from 500 to 800 m above the crater, indicating that the "muzzle" velocity of these eruptions was between 98 and 127 m/sec. At the lower figure, a block of rock that has reached its highest point will fall for about ten seconds before hitting the flank of the cone, in contrast to about 13 sec for the higher figure. These velocities are comparable to those measured during the first year of the Volcano's activity, when bombs were rarely observed to require more than 11 or 12 sec to fall from the tops of their arcs. At present, however, the periods of such strong activity are short-lived and infrequent, whereas in the first year they were of long duration and were interrupted by only short intervals of moderate to weak activity. Moreover, the average diameter of the eruptive vent is now considerably less than in 1943, and hence the volume of material erupted by equally strong explosions is now smaller.

The average volume of pyroclastic material erupted from the Volcano has apparently continued to decline (see Tables 1 and 2). At Equijuata station, only 3.9 mm of ash fell in the second half of 1950, as compared with 4.1 mm in the corresponding period of 1949 [see FRIES and GUTIERREZ, 1950, Table 3]. The ashfall at Cuezeno station was only 2.1 mm, of which a small part may have consisted of wind-blown surface ash collected by the gage, particularly during the dry months of November and December when dust storms were frequent.

Form of the cone and crater--Parícutin cone had much the same exterior form at the end of December 1950 as in the preceding June. It continued to present a three-pointed profile as seen

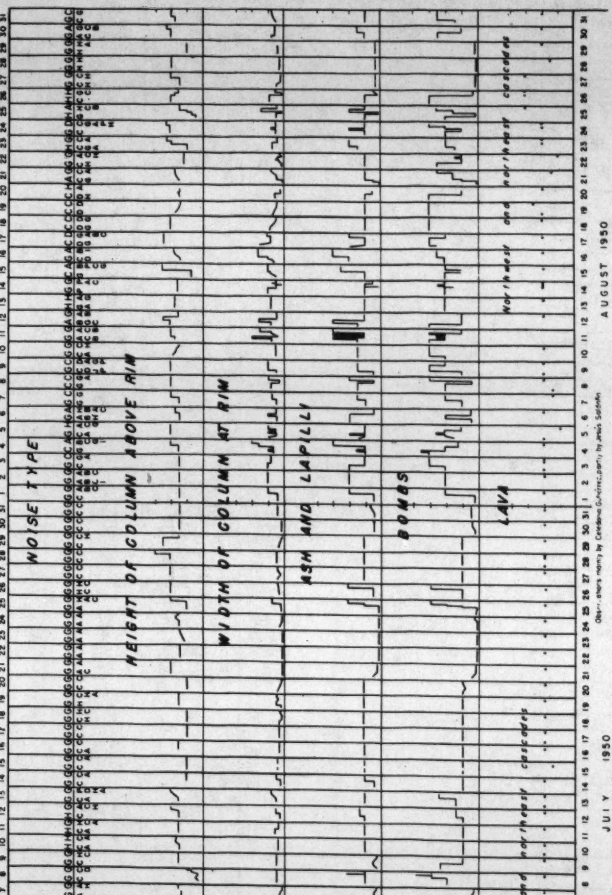


Fig. 1.--Eruptive characteristics of Parícutin Volcano from July 1 to August 31, 1950

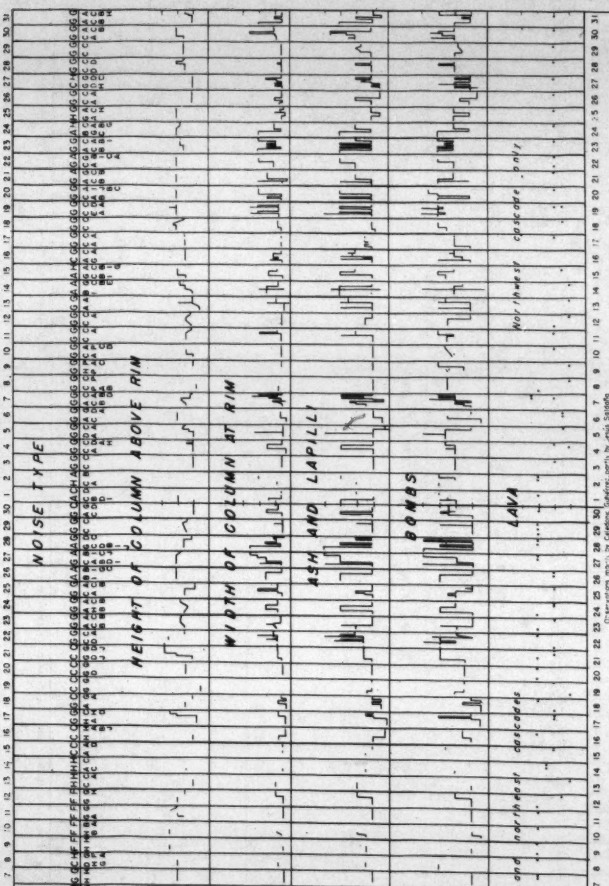


Fig. 2--Eruptive characteristics of Parícutin Volcano from September 1 to October 31, 1950

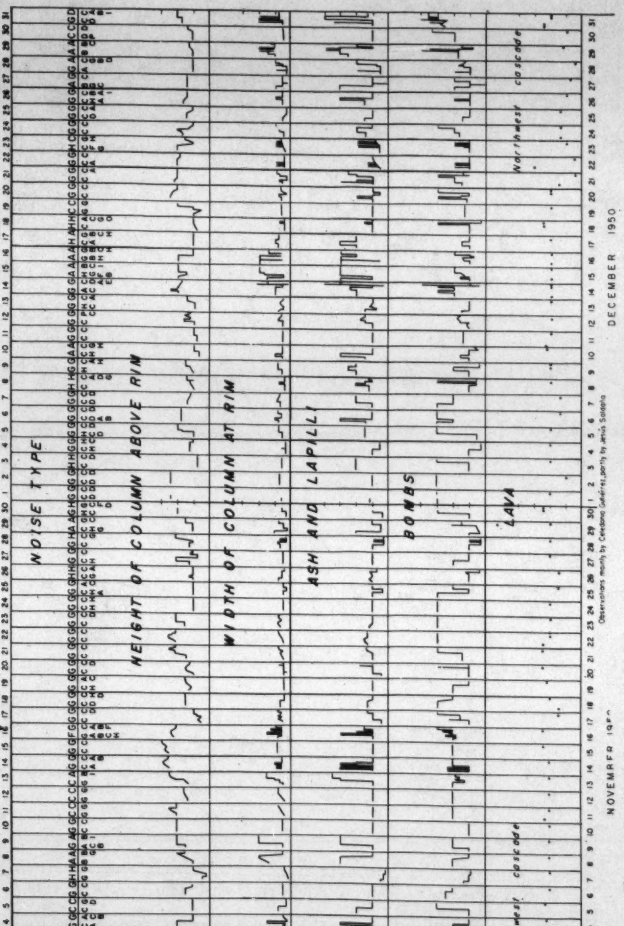


Fig. 3--Eruptive characteristics of Paricutin Volcano from November 1 to December 31, 1950

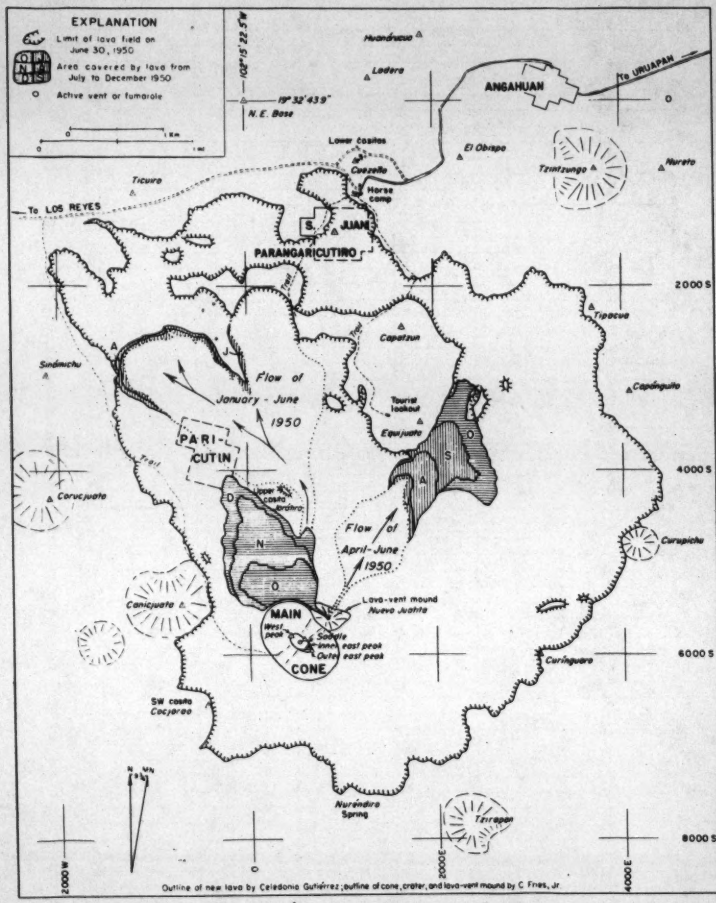


Fig. 4--Areas covered by Paricutin lava flows from July 1 to December 31, 1950

from the north, although the northeast saddle was relatively less conspicuous and the inner east peak was nearly as high as the west peak. No change was noted on the southwest side of the cone, except for a more rounded appearance due to the accumulation of pyroclastic material. On November 19 a hole blew open near the center of the saddle in the northeast rim of the cone. Although this was sealed almost immediately, the northeast flank continued to slump slowly during the next two weeks. New material erupted from the crater, however, had healed these wounds by the end of December.

Fig. 5--Multiple, relatively quiet, heavily ash-and-bomb laden eruptions emerging from northeast-southwest fissure in Paricutin crater on December 29, 1950, as seen from northwest rim of cone

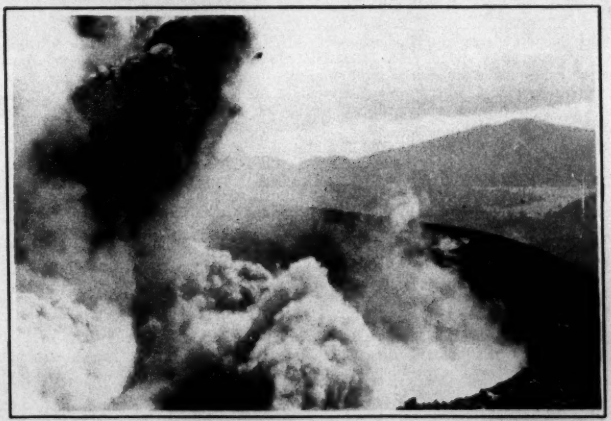


Fig. 6--Southwest saddle and south rim of Paricutin cone on December 29, 1950, showing ash-and-bomb laden eruption from bottom of crater, as seen from northwest rim

The coordinates of triangulation stations around the Volcano were replotted on a new base and the outline of the cone was redetermined in October by intersection from these known stations. From this new map the horizontal distances to points on the cone and to the lava vent were remeasured (see Table 3). The top of the cone was found to have shifted toward the southeast, probably because of the greater accumulation of pyroclastic material in that sector and the gradual burial and obliteration of the main northeast eruptive throat of the crater in the past year or two.

Table 1--Monthly summaries of weather observations, rainfall, and ashfall near Parícutin Volcano

Month	Cuezeño station							Equijuata station	
	Temperature		Rainfall		Ashfall		Min. humidity	Average direction of upper winds	Rainfall (total)	Ashfall (total)
	Max.	Min.	Total	Max.	Total	Max.				
	°C	°C	mm	mm	mm	mm	pct		mm	mm
July	23.6	7.8	314.6	60.5	tr	tr	...	E	403.7	0.8
August	23.1	8.3	229.9	28.8	0.0	0.0	...	E	368.3	0.8
September	23.3	8.3	222.7	21.0	0.5	0.3	67	E	248.7	1.0
October	24.4	2.8	108.0	34.0	0.0	0.0	31	E and W	90.0	0.0
November	25.0	1.9	9.3	3.0	1.2	1.0	...	ENE and W	46.5	0.5
December	25.0	1.1	4.8	4.8	0.4	0.3	...	E and WSW	10.0	0.8

Table 2--Rainfall and ashfall at Cuezeño and Equijuata stations for yearly periods from January 1947 to December 1950

Period	Cuezeño station		Equijuata station	
	Rainfall (total)	Ashfall (total)	Rainfall (total)	Ashfall (total)
	mm	mm	mm	mm
Jan.-Dec. 1947	1479.9	42.6	.....	.....
Jan.-Dec. 1948	1710.8	12.3	.....	.....
Jan.-Dec. 1949	1355.2	8.7	1593.9	16.8
Jan.-Dec. 1950	1315.0	7.2	1761.5	11.6

Inasmuch as a precise base had not been used for determining distances for several years, the shift may have occurred little by little over a period of four or five years. The base of the cone was found to measure 940 m from northwest to southeast and 600 m from northeast to southwest. The latter dimension is even less than it was six months ago, as lava from the northeast Nuevo Juatita vent has gradually been covering the lower flank on that side. The crater rim measured 220 m from northwest to southeast, between the west peak and the inner east peak, although the rim extended 50 m farther to the southeast, out to the outer east peak. The crater diameter from northeast to southwest was only 140 m.

Using the new horizontal distances given in Table 3, the changes in altitude of points on the cone, as determined by alidade from Cuezeño station, were calculated and are shown in Table 4. The effect on altitude of the shift in position of these points is distributed over the three sets of figures given, so that the full effect appears only in the final set for December 28. The estimated accuracy of these most recent determinations is ± 2.0 m, assuming an accuracy of ± 10 m for the

Table 3--Redetermined horizontal distances[a] from Cuezeño station to points on Parícutin cone

Point sighted[b]	Horizontal distance formerly measured	New horizontal distance (Oct. 1950)
	m	m
West peak	5160	5200
Lowest point on northeast rim	5160	5220
Outer east peak	5270	5330
Inner east peak	5240	5300
Lava-vent mound	4950	4970

[a]Estimated accuracy of ± 10 m.
[b]See Figure 4 for location of points.

Table 4--Elevation[a] above sea level of points on Parícutin Volcano

Date	West peak	Lowest point on northeast rim	Outer east peak	Inner east peak	Lava-vent mound
	m	m	m	m	m
August 31	2799.5	2771.4	2777.8	2784.0	2663.0
October 23	2802.5	2776.4	2781.3	2789.2	2666.4
December 28	2805.4[b]	2780.0[b]	2784.9[b]	2795.9[b]	2668.5[b]

[a]Determined by alidade from Cuezeño station.
[b]Estimated accuracy of ± 2.0 m.

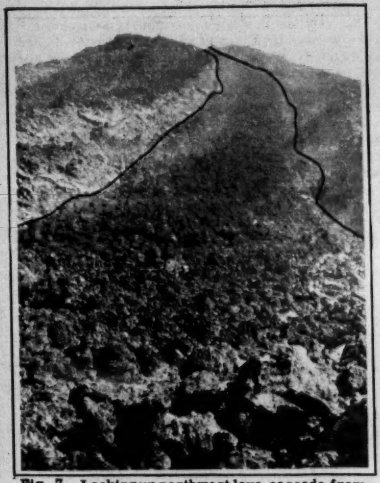


Fig. 7--Looking up northwest lava cascade from its base on December 29; flow is so sluggish that picture was taken eight meters out from edge of moving lava; black mass in upper left part of picture is result of flooding

horizontal distances used and ± 0.5′ for the angles measured. Comparing these figures with those for December 31, 1946 [see WILCOX, 1947, Table 1], the west peak has risen 52 m in the past four years, and the highest point on the east rim has risen 37 m.

When the senior author ascended the cone on July 7, the bottom of the crater was a bowl about 25 m deep, elongated in a northwest-southeast direction and pierced by eruptions near its southeast end. The junior author ascended the cone on July 18 and found the crater to be about 20 m deep, relative to the northeast saddle. Eruptions came from a throat about nine meters in diameter located on the northwest side of the bottom of the bowl. A second throat about ten meters to the southeast was filled and glowing red. On another ascent on August 27, the junior author found the crater to consist of a roundish bowl with a single eruptive throat in the center. The southeast wall of the crater was fractured and appeared to be slumping.

On December 29 the authors found the crater bottom to be elongated in a northeast-southwest direction, or at right angles to the elongation of the past seven or eight months. Although the eruptions were intense and heavily laden with ash and bombs (see Fig. 5 and 6), the throat could be seen at times between explosions to consist of a fissure about three meters wide and perhaps 20 m long. Eruptions issued from different parts of the fissure at different times, although occasionally they came from several parts of the fissure at the same time. The bottom was about 25 m below the northeast saddle. The only terrace present late in December was between the outer and inner east peaks; it had a maximum width of 50 m and sloped from the crater lip toward the outer east peak. The southwest saddle seemed to be a few meters higher than the northeast saddle.

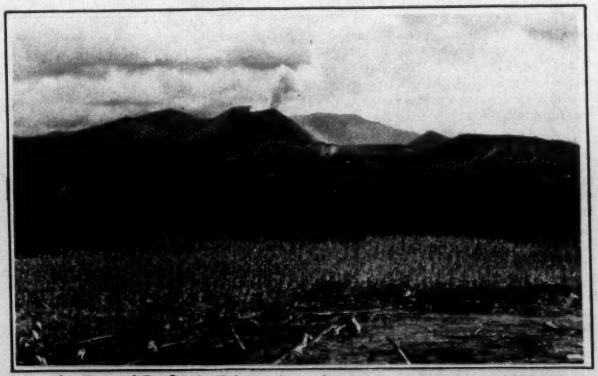


Fig. 8--View of Parícutin Volcano from the northeast in October 1950; corn planted around and over lava of 1944 produced a profitable yield for the first time since the Volcano's birth

Activity of the lava vents--The only point of lava issue during the period was the Nuevo Juatita vent at the northeast base of the cone. This vent has now been continuously active for nearly three years. Periodic floodings around the point of lava issue have built the cone higher by about five meters in the past six months [see Table 4], or at a rate about equal to that of each of the last three six-month periods. Lava flowed in two cascades, one to the northeast and the other to the northwest, until October 12, when strong flooding permitted it to break through a little farther to the west and at a lower level (see Fig. 4). This beheaded the flow to the northeast, and all the lava then descended to the northwest. Cutting off the feed to the northeast cascade permitted the steep channel to be emptied and to show the characteristic, nearly vertical walls and the five- to seven-meter depth of such channels. Gas eruptions from the vent were noted only on July 27, and a small incipient fountain was observed for a few minutes on September 27. Lava emission was otherwise quiet and generally very sluggish. On December 29 the flow at the base of the northwest cascade was so sluggish that one could walk out on the lava as far as ten meters from its edge (see Fig. 7). The volume of fumes given off by the fresh lava is now considerably less than in former years, making observation correspondingly easier.

Activity of the lava flows--The flow from the northeast cascade continued to move along the base of Equijuata until late in October, when it came to rest as a result of beheading. It had covered two small islands of old ground and a part of the base of Equijuata (see Fig. 4). The flow from the northwest cascade continued to pile up at its front to the east of Sinámichu station, advancing a little beyond its position in June. The outbreak of October 12 beheaded this flow also, and the route of the new lava was west of that of the previous flow, mainly over the older, ash-covered flows. The front of this new flow had advanced about 1900 m by the end of December. No marked difference was noted in the character of these flows as compared with those of the past several years.

The area covered by new lava during the second half of 1950 amounted to about 2,080,000 sq m, as determined by measurements with a planimeter. The average thickness of this lava is estimated to be at least eight meters, ranging from perhaps four meters near the base of the cascade to about 20 m at the northwest front. The volume of lava extruded during the six-month period was therefore about 17,000,000 cu m. This was notably smaller than that of any earlier six-month period on record, and the average daily volume was less than half that of 1948.

Weather data--Rainfall during the second half of 1950 was as usual considerably less at Cuezeño station than at Equijuata station (see Table 1). A comparison of the yearly totals shows that rainfall at Cuezeno was less in 1950 than in 1949, but at Equijuata it was greater in 1950 than in 1949 (see Table 20. Records do not go back far enough in time to indicate any constant trend that might be correlated with the declining activity of the Volcano, although the suggestion continues to be that no relation exists between precipitation and eruptive activity.

Since the ashfall has declined so markedly in the past four years, agriculture is gradually advancing into areas closer to the cone and even around and over the new lava, in places where old soil mixed with new ash has been washed against and over the lava. Figure 8 is a photograph of a large cornfield near Tipacua (see Fig. 4), where for the first time a profitable yield of corn was harvested in the fall of 1950. The region from Zacán westward has been washed sufficiently by the rains to remove most of the ash cover and to permit nearly normal agriculture once again. People have been moving back into the villages in that region, and the livestock population has risen sharply because of reviving pasturage. No disastrous floods have occurred in that region for five years or more, and the devastated plains at Los Reyes have been returned to cultivation.

Acknowledgments--Observations at Parícutin are being carried on cooperatively by the United States Geological Survey and the Comisión Impulsora y Coordinadora de la Investigación Cientifica of the Mexican Government. The Geological Survey received its funds from the Interdepartmental Committee on Scientific and Cultural Cooperation of the Department of State until October, when the burden was shifted to the Point IV program. The salaries and expenses of the authors were carried by the Geological Survey, and those of the junior author's assistant, Jesús Saldaña, were paid by the Mexican Comisión Impulsora, through Ricardo Monges López, whose close cooperation is highly valued. The authors appreciate the services of José Lauro Ramírez in the tedious work of drafting the diagrams and lava map, and they are indebted to Ray E. Wilcox and Kenneth Segerstrom for helpful critical comments.

References

FRIES, CARL, JR., and CELEDONIO GUTIERREZ, Activity of Parícutin Volcano from July 1 to December 31, 1949, Trans. Amer. Geophys. Union, v. 31, pp. 732-740, 1950.

FRIES, CARL, JR., and CELEDONIO GUTIERREZ, Activity of Parícutin Volcano from January 1 to June 30, 1950, Trans. Amer. Geophys. Union, v. 32, pp. 212-221, 1951.
WILCOX, RAY E., Activity of Parícutin Volcano from December 1, 1946 to March 31, 1947, Trans. Amer. Geophys. Union, v. 28, pp. 725-731, 1947.

U. S. Geological Survey,
Lafragua 18,
México, D. F., México

(Communicated manuscript received April 23, 1951;
open for formal discussion until January 1, 1952.)

Transactions, American Geophysical Union Volume 32, Number 4 August 1951

SOIL ANISOTROPY AND SOME FIELD METHODS FOR MEASURING PERMEABILITY

Ronald C. Reeve and Don Kirkham

(Journal Paper No. J-1823, Iowa Agricultural Experiment Station, Ames, Iowa, Project 998)

Abstract--Three field methods--piezometer, auger hole, and tube--and the conventional undisturbed-core method for measuring soil permeability are compared theoretically and experimentally. Natural channels in the soil, such as cracks, roots, and worm holes, cause extreme variations in results by the undisturbed core method and cause the rate of rise, in small-diameter piezometers, to deviate from the theoretical. This deviation becomes negligible as the pipe diameter is increased. The size of sample associated with each method differs from one method to the other. In non-uniform soils this causes differences in measured permeability values. In anisotropic soils the piezometer and auger methods, using the usual inflow cavities which are long compared to their diameter, measure essentially the horizontal permeability; whereas the tube method, where length of cavity equals zero, measures essentially the vertical. The undisturbed-core method may be used to measure either the horizontal or vertical permeability depending upon the direction in which the cores are taken. The piezometer method appears to be convenient and valuable for general use because of its suitability for measurement of permeability at any depth in both uniform and non-uniform soils. The auger-hole method is well adapted for measuring permeability in unstratified soils and appears particularly advantageous in soils having many root holes and other natural channels. The tube method, a special case of the piezometer method, with large diameter and a cavity length of zero, is especially useful in measuring essentially the vertical permeability of anisotropic soils. All the methods as described here apply to water-saturated soil below a water table. The core method in its application to unsaturated soil, where it is perhaps most useful, is not a part of this study.

Introduction

The measurement of the permeability of soil in its natural water-saturated state, that is, when a water table is present, is of fundamental importance in the rational solution of drainage problems. Three methods for making this type of measurement have been described by LUTHIN and KIRKHAM [1949], FREVERT and KIRKHAM [1948], and VAN BAVEL and KIRKHAM [1948]. In the present paper some theoretical and experimental comparisons are made of these methods and of the conventional undisturbed-core method. By an undisturbed core is meant one which has

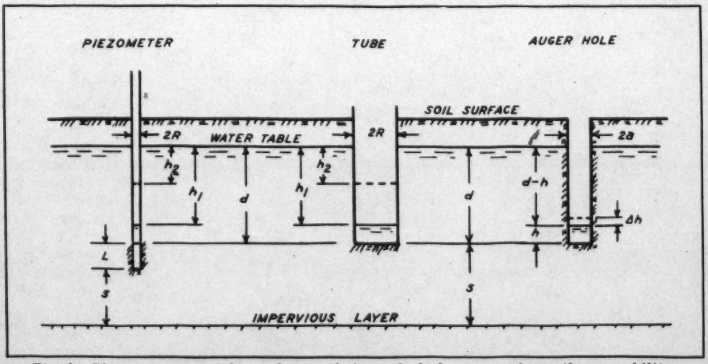


Fig. 1--The piezometer, tube, and auger-hole methods for measuring soil permeability; conventional undisturbed-core method not shown

been obtained, in cylindrical form, with a round core-cutter, designed to produce a minimum of disturbance in the sample.

The three field methods are represented in Figure 1. In all three methods there is first made, with minimum soil disturbance, a cavity below the water table; next, the cavity is allowed to fill with water and is then pumped out a few times with a small portable hand pump until any puddled-over water passages terminating in the cavity have been flushed out by the inseeping water; next, the natural water-table level is measured after it has been allowed sufficient time to establish itself in the cavity; finally, the water level is pumped down in the cavity, the rate of rise observed, and this rate of rise reduced to standard permeability units by means of a suitable formula.

In the piezometer method, water seeps into a cylindrical cavity at the base of an unperforated thin-walled pipe; in the tube method, water seeps upward over a horizontal soil surface at the base of a thin-walled tube; and in the auger-hole method, water seeps into the sides and bottom of an uncased auger hole. Piezometer cavities in the present tests were generally one inch in diameter, tube cavities, eight inches; and auger holes, four inches. The core samples in the present experiment were two inches in diameter and two inches long, and in all cases were taken in the vertical direction from an auger hole below the water table.

The tube and piezometer methods are basically the same since both were derived from the same ground-water flow solution [KIRKHAM, 1945], but are considered separately here because of important differences in equipment and techniques for making permeability measurements. The inflow cavity of the tube method corresponds to a piezometer cavity of large diameter and zero length.

The appropriate formulas for reducing observed quantities in the three methods to standard permeability units are (taking K as the permeability, $(t_2 - t_1)$ the time for water to rise from level h_1 to h_2, and other symbols as in Fig. 1)

$$\text{For piezometer and tubes} \qquad K = \left\{\pi R^2/[A(t_2 - t_1)]\right\} \log_e (h_1/h_2) \quad \ldots\ldots\ldots (1)$$

$$\text{For auger hole} \qquad K = [\pi a^2/(d - h)A]\,(\Delta h/\Delta t) \quad \ldots\ldots\ldots\ldots\ldots (2)$$

taking Δt as the time for water to rise a distance Δh in the auger hole.

The quantity A, the A-function, is a geometrical constant which varies from method to method, and has the dimensions of a length.

If for piezometers, as is generally true in practice, $d >> L$, $s >> L$ (see Fig. 1), then the A-function in inches may be read for piezometers from Figures 2 and 3 of LUTHIN and KIRKHAM [1949] (in the latter authors' Fig. 4, the axis of ordinates should be labeled 0, 8, 16, 24, instead of 0, 4, 8, 12, but their Fig. 2 and 3 are correct); furthermore, the A-functions read from these figures will be approximately correct even if s is not large compared to L. Values of the A-function in inches for tubes may be read from Figure 3 of FREVERT and KIRKHAM [1948]. Values of the A-function for auger holes, when s of Figure 1 is zero, may be determined from Eq. (23) of KIRKHAM and VAN BAVEL [1948]

$$A = 16adS/(d - h)\pi \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

where a, d, and h are as in the present Figure 1, and S is a multi-term dimensionless function of h/d and a/d, defined by their Eq. (11). Numerical values of S may be read from Figure 6A of KIRKHAM and VAN BAVEL [1948]. If the auger-hole depth d is large compared to its radius a, the effect of the soil below the auger hole on flow may be ignored. That is, for $d >> a$, one may consider $s = 0$ and hence may use Eq. (3) to obtain values of A-functions. If d is not large compared to a, values of A, for $h/d = 0$ and $h/d = 0.5$ for several values of s/d, may be read from Figure 4 of VAN BAVEL and KIRKHAM [1948]. Recently charts have been prepared and made available in limited number by the Agricultural Experiment Station and Soil Science Institute, Groningen, The Netherlands, for converting field observations with the auger-hole method directly to permeabilities.

In the piezometer and tube methods, A is not a function of h_1 or h_2; in the auger-hole method, A is a function of h. In the auger-hole method, the average value of A for the range of increment Δh may be used, and Δh is to be taken small compared to $d - h$. The dimensions of K will be inches per hour, if A, d, h, etc., are all specified in inches, and the time in hours.

Different sizes and shapes of samples are involved in the four methods. By size of the sample is here meant the volume of soil through which the water moves in a single permeability measurement. In the core method, the size of the sample is the finite volume of soil contained in the core; in the present case, $\pi \times 1^2 \times 2$ cubic inches. In the three field methods, the size of sample is theoretically the infinite volume of soil surrounding the cavity. Practically speaking, the size of sample in the field cases may be taken rather arbitrarily as that volume of soil in which 80 per cent of the hydraulic head is dissipated. This volume may be calculated from flow nets presented in the three references cited at the outset of this paper. If the volume of soil in the core sample is taken as unity, then, on the 80 per cent basis, the sizes of sample for core, one-inch piezometer, eight-inch tube and four-inch empty auger hole, at a common depth of 30 inches, are in the ratio 1, 35, 270, 1400. For practical depths other than 30 inches and for a partly filled auger hole, the ratios will be about the same. Shapes of the samples are shown in Figure 2.

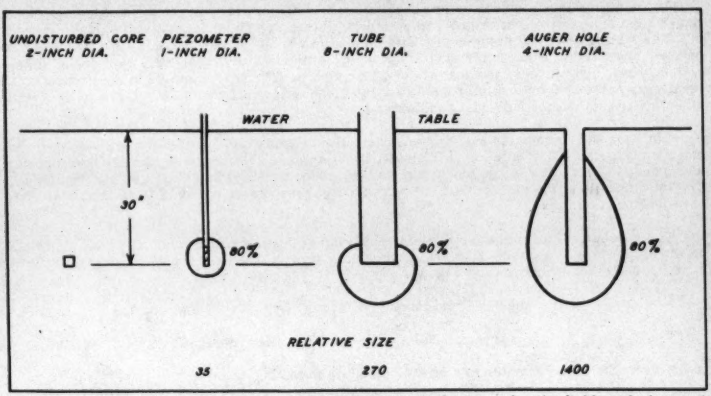


Fig. 2--Relative sample sizes for four permeability methods; sizes for the field methods are the volumes of soil through which 80 per cent of the hydraulic head is dissipated

Results

Field tests--Tests of the methods were made at five sites. Data from two of the sites, 1 and 2, bring out pertinent findings (see under Discussion) and will be presented in some detail. Site 1 (see Table 1) will first be considered. Here the bottoms of the soil cavities for piezometers, tubes, and auger holes were 18 inches below the soil surface. Since the size of the sample for each of the field methods is many times larger than that for the core method, core samples were taken at this site from two depths, 14-16 and 20-22 inches, to correspond to the region immediately around the cavities of the several field methods. All soil cores were taken from below the water table and were maintained in a completely saturated condition until the laboratory permeability tests were completed. At all depths mentioned, except for one location at 20-22-inch depth, root holes, generally less than two mm wide, permeated the soil. The presence of root holes is noted since root holes in agricultural soils introduce a major problem in determining an effective soil permeability. The positions for measurements at Site 1, and other sites, were laid out in a randomized block design, with the blocks six feet on a side. There should be negligible interaction in measured values with this arrangement [see FREVERT and KIRKHAM, 1948].

Table 1 shows that the piezometer, auger-hole, and tube methods yield respectively permeabilities of 24.4, 14.4, and 9.18 in/hr; whereas the core-sample method yields an average value of $(21.4 + 39.1)/2 = 30.2$ in/hr. The very low value 0.13 in/hr at position 6 was included intentionally in the average because it is the experience of the authors that occasional spots of low permeabilities can occur in otherwise highly permeable soil of uniform appearance. Examination of the particular low-permeability core in question revealed that it contained no visible root holes. All other cores contained many. Position 6 was a random position in the block.

At Site 2 (Table 2) there are no root holes. This is in contrast to the many root holes at Site 1.

Table 1--Soil permeability[a], as determined by the auger-hole, piezometer, tube, and undisturbed-core methods, on a sandy loam[b] containing many root holes (Site 1)

Method	Inside diameter	Depth[c]	1	2	3	4	5	6	Average	Coefficient of variation
	inch	inch	in/hr	in/hr	in/hr	in/hr	in/hr	in/hr	in/hr	
Piezometer[d]	1	14-18	34.00	27.60	24.55	11.40	.....	.....	24.4	19.5
Auger hole	4	4-18	17.70	15.00	14.55	10.27	.....	.....	14.4	10.7
Tube	8	18	5.71	11.30	9.87	9.84	.....	.....	9.18	13.2
Undisturbed core	2	14-16	31.6	24.0	7.5	16.0	14.2	35.3	21.4	20.5
Undisturbed core	2	20-22	38.2	86.7	40.4	41.6	27.4	0.13[e]	39.1	29.3

[a]Readings corrected to 20°C.
[b]Recent glacial outwash material near Clear Lake, Iowa.
[c]Depths are referred to soil surface, and for the field methods indicate the extremities of the respective inflow cavities; water table is at four-inch depth.
[d]Cavity at base of piezometer four inches long.
[e]This sample contained no root holes whereas all other samples had many.

Table 2--Soil permeability[a], as determined by the auger-hole, piezometer, tube, and undisturbed-core methods, on a sandy loam[b] in which there are no root holes (Site 2)

Method	Inside diameter	Depth[c]	1	2	3	4	5	6	Average	Coefficient of variation
	inch	inch	in/hr	in/hr	in/hr	in/hr	in/hr	in/hr	in/hr	
Piezometer[d]	1/2	16-20	6.05	5.69	3.56	2.02	7.12	3.90	4.72	16.3
Piezometer[d]	1	16-20	4.34	5.32	4.39	6.17	1.52	5.10	4.47	14.5
Piezometer[d]	2	16-20	4.16	5.73	4.62	3.67	2.53	2.13	3.81	14.4
Auger hole	4	4-20	2.79	5.34	5.97	3.80	2.64	3.38	3.99	14.0
Tube	8	20	0.23	2.39	0.89	2.48	0.31	0.12	1.07	42.1
Undisturbed core	2	12-14	0.012	0.040	0.180	0.086	0.002	0.310	0.105	46.7

[a]Readings corrected to 20°C.
[b]Recent glacial outwash material near Little Wall Lake, Jewell, Iowa.
[c]Depths are referred to soil surface and for the field methods indicate the extremities of the respective inflow cavities; water table is at four-inch depth.
[d]Cavity at base of all piezometers is four inches long.

At Site 2, in addition to the permeability values obtained with the one-inch piezometers, eight-inch tubes, four-inch auger holes, and two-inch soil cores, as at Site 1, there were obtained permeability values using half-inch and two-inch piezometers. As seen in Table 2, the permeability values appear to decrease as pipe diameter increases. The half-, one-, and two-inch pipes yield respectively, 4.72, 4.47, and 3.81 in/hr. This apparent decrease in permeability with pipe diameter for Site 2 is shown in Figure 3. The auger-hole value 3.99 is approximately the same as the average piezometer value, namely (4.72 + 4.47 + 3.81)/3 = 4.33 in/hr. The values for the tube (1.07 in/hr), and the core method (0.105 in/hr) are decidedly lower than all others. In Figure 3 the abscissa is actually not pipe diameter, but is pipe radius divided by length of cavity. Since, however, the length of cavity is in each case four inches, the abscissa may be taken as a measure of diameter of cavity. The decrease in permeability appears to be linear with diameter of cavity.

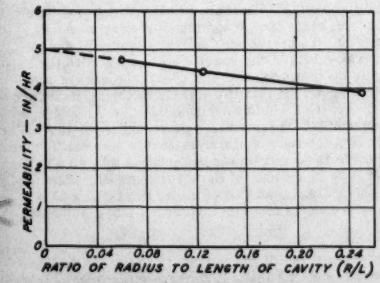


Fig. 3--Apparent linear decrease in permeability with ratio of radius to length of piezometer cavity

At two of the five sites studied, one of which is Site 1 for which data are presented, it was observed, in the case of small-diameter piezometer measurements, that a plot of $\log_e h_2$ versus t_2 did not yield a straight line as it should according to Eq. (1). Values of h_2, at times t_2, were always larger than they should

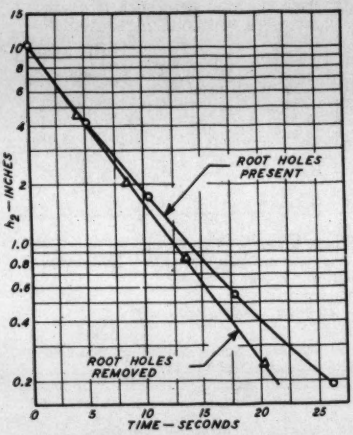


Fig. 4--Effect of root holes as simulated in a laboratory sand-tank model for the piezometer case; the value h_2 is the effective hydraulic head (see Fig. 1)

be. In other words, the piezometer did not fill as rapidly as it should according to the theory. The effect was especially noticeable for piezometers of sizes smaller than one inch in diameter and occurred only if there were root holes in the soil.

Laboratory test--In order to determine whether root holes were the cause of the apparent decrease in permeability with decreasing head, h_2, a sand-tank model test was made in the laboratory. A one-inch piezometer with a three-inch, cylindrical, screened opening at its base was placed in a sand tank 13 inches in diameter and 16 inches high. Root holes were simulated by placing vertical perforated copper tubes 1/4 inch in diameter in the tank before filling with sand. The copper tubes were located 3 1/4 inches apart at the points of a rectangular grid; the piezometer was at its center. The tank was perforated, and a screen wrapped around it. The whole assembly was placed in a large constant-level water tank. Water entered the sand both from the circumference and from the top. The (constant) potential of input water closely corresponded to the 95 per cent equipotential shown in Figure 5 of LUTHIN and KIRKHAM [1949]. The tank arrangement was designed for water to enter from the 95 per cent equipotential surface in order to reduce the size of model. Strictly speaking, if the 100 per cent equipotential were used for introducing water into the sand, a model of infinite size would be needed to simulate the field case.

Figure 4 shows typical curves of the relationship of log h_2 to t for the sand tank with and without root holes. The rate of rise was in accordance with the theory when no root holes were present in the sand, as indicated by the straight line (Fig. 4), but with root holes present the relation between $\log_e h_2$ and t became curvilinear, as was observed in the field. The curves bring out another important point. The slope of the curves at t = 0 is about the same both with and without root holes. It appears, thus, in converting rate-of-rise data for small-diameter piezometers in soils with many root holes, that the initial portion of the curve should be used. This was done in this study; although it will appear in the discussion that non-linear curves of the relation of $\log_e h_2$ to t should be avoided. They can be avoided by use of large-size piezometers, as will be seen later.

Discussion

Considering at Site 1 the core samples at the depth of 14-16 inches, which was approximately the depth of piezometer measurements, it would seem, since the piezometer and core methods yield essentially equal values, 24.4 and 21.4 in/hr, that the piezometer and core methods are the correct ones. One could also reconcile the lower value 14.4 of the auger-hole method with the 24.4 and 21.4 values of the piezometer and core methods by reasoning that the soil at the base of the auger hole was really of permeability 21.4 (or 24.4) in/hr, but that the soil above the 14-inch core sample depth was of permeability less than 21.4 in/hr. One would then conclude that the average value of seepage for the whole length of auger hole would correspond to a permeability of 14.4 in/hr. The above considerations would appear justifiable if there were a plausible reason for omitting the 9.18 value as measured by the tube method. But there is no reason for discounting this 9.18 value even though it is less than one-half of the value 24.4 or 21.4 in/hr of the other methods. Furthermore, the coefficient of variability for the 9.18 value is less than that of either the 24.4 or 21.4 values, as is shown in Table 1. It appears that a new concept must be introduced into the discussion to resolve discrepancies.

Soil anisotropy--A plausible explanation for the observed discrepancies in the permeability values at Site 1 (and Site 2) may be obtained by postulating that the soil at these sites is anisotropic, the anisotropy being such that the horizontal permeability is greater than the vertical permeability, a condition common in soils [CASAGRANDE, 1937]. The general theory of water movement in

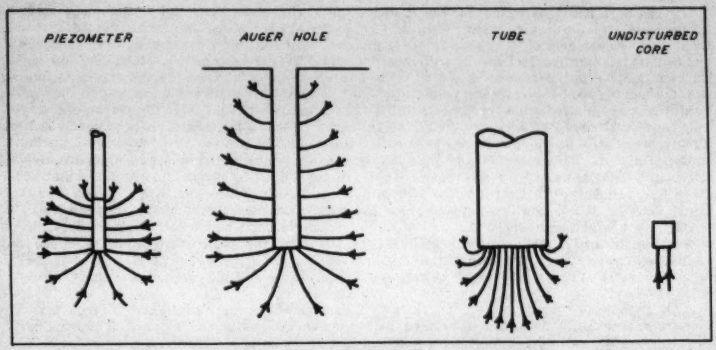


Fig. 5--Schematic flow lines for four permeability methods; horizontal flow is dominant in the piezometer and auger-hole methods; vertical flow, in the tube method and undisturbed cores which were taken vertically in the present study; flow lines for the auger-hole method are indicated for the case that the hole is about half full of water

anistropic soils has been given by VREEDENBURGH [1936]. The effect of anistropy has not been included so far in the theoretical development of the three field methods under study here.

With the anisotropy postualte in mind one may consider the manner (see Fig. 5) in which flow enters a piezometer cavity, an auger hole, and a tube cavity. In the case of the piezometer cavity, since the cavity is long compared to its diameter, most of the inflowing water enters horizontally. Horizontal flow is likewise largely dominant about the auger hole, especially if the ratio of length to diameter is large and if, for a permeability measurement, the hole has not been pumped down too far. There is opportunity for a vertical component of flow to occur immediately next to the auger hole because the portion of the wall above the pumped-down water level in the hole is a surface of seepage, that is, a surface where the hydraulic head decreases linearly with vertical distance along the surface. The manner in which flow enters a surface of seepage is shown in Figure 4 of KIRKHAM and VAN BAVEL [1948] and Figure 6 of VAN BAVEL and KIRKHAM [1948]. Thus the piezometer and auger-hole methods should tend to measure horizontal flow. The tube method, on the other hand, should tend to measure vertical flow, because, as seen in Figure 5, the flow in the region of soil near the base of the tube where 80 per cent of the hydraulic head is dissipated is largely vertically upward. The piezometer and auger-hole values of permeability are higher at both Sites 1 and 2 than the tube values.

The piezometer data for Site 2 support the concept of anisotropy as used above to interpret the permeability values. If one observes the flow lines for the piezometer cavity as shown in Figure 5, one sees that the shorter the cavity is, compared to its diameter, the smaller should be the accentuation of horizontal flow as compared to vertical flow. In fact, if R is the radius of a piezometer cavity and L its length, one might expect in an anisotropic soil of the type described above, in which the horizontal permeability is greater than the vertical, that the measured permeability value would decrease as the ratio R/L increases. This, as shown in Figure 3, appeared to be the case at Site 2, the decrease seeming to be an accurate straight-line relation when average permeability values are plotted against R/L. Consideration of the data from all the methods in Table 2 also appears to bear out the anisotropy concept for Site 2. According to theory, the horizontal flow is favored first by piezometer cavities which are long compared to their diameter, next by an auger-hole cavity; horizontal flow is not favored by the tube and least, or not at all, by the vertical soil cores. Thus in Table 2 one should expect the permeability values to fall off from top to bottom, and this is what they do. The data are not complete enough to say whether the two-inch piezometer or the four-inch auger hole are in correct order, but it is remembered that the cavity of the two-inch piezometer, being two inches in diameter, is not long compared to its diameter. At Site 2 the depths of cores may not be considered to be strictly comparable to the depth for other methods, but there was no apparent stratification at this site. If for depth considerations the undisturbed-core values are omitted, the data for the five other independent measurements (see Table 2), which appear to be in agreement with the anisotropy concept, still remain.

It has been noted above that the curve of Figure 3, where averages are plotted, appears to be an accurate straight-line relation. This, in view of the scatter of the data, must be considered fortuitous. Nevertheless, the curve is presented just as it fell, for it pointed up to the writers, and illustrates an important theoretical consideration. This consideration, which depends on Darcy's law, but is independent of any of the present experimental data, may be stated as follows. If, for a homogeneous soil, having relatively high horizontal permeability compared to the vertical, there are plotted measured permeability values versus (R/L)-values for piezometer cavities, there will result a curve of negative slope; furthermore, a measured value of permeability for a value of R/L which approaches zero will approach the true value of the horizontal permeability of the soil. Thus, for Figure 3 the true horizontal permeability would be approximately five in/hr. Detailed proof for the above consideration need not be given. Its truth becomes evident if one recognizes that most of the drop of head, in the soil water reaching a piezometer cavity, occurs, due to flow convergence, near the cavity; and that, furthermore, only the flow which is both near the cavity, and near the cavity at its ends, has an appreciable vertical component. Accordingly, the loss in energy of the fluid entering the whole cavity must be, in the limit as R/L approaches zero, that due only to horizontal flow. In this argument the cavity referred to is the water-filled opening of length L and radius R at the base of the piezometer tube.

Although a piezometer cavity, for which R/L approaches zero, should yield the true horizontal permeability, it is emphasized here that a piezometer cavity, for which R/L approaches infinity, does not yield the true vertical permeability of the soil. A piezometer for which R/L approaches infinity is the so-called tube of this paper. For this type of piezometer the accentuation of vertical permeability should be the same for all tubes, independently of their diameter, provided measurements are made at a depth large compared to the diameter of the tube.

Root holes and soil permeability--At Site 1 (Table 1) the average measured values of the permeabilities fall off from top to bottom, as at Site 2, except for the core samples. Since the cores were taken in the vertical direction and since the soil at Site 1 is a recent glacial outwash material, presumably of relatively high horizontal permeability, as at Site 2, one would expect, on the basis of soil anisotropy, that the core permeabilities would be lower than for each of the other methods. A possible explanation that at Site 1 the core values were generally higher than for the other methods may be obtained by consideration of the flow paths associated with each method and the presence of many vertical root holes. All cores, except one, had many vertical root holes and some of these passed light completely through the core. These channels for the undisturbed cores thus comprised vertical flow paths of high velocity connecting the inflow surface of high hydraulic head to the outflow surface. Vertical flow paths, as from vertical root holes, continuous between the surface of high hydraulic head (water table) and the outflow surface (soil cavity), cannot exist in the piezometer, tube, or auger-hole methods. This is apparent from Figure 1 where one sees that no portion of the outflow cavity in any of the latter methods is directly below the water table. There is a conceivable exception. Vertical channels immediately next to the piezometer or tube could comprise paths of vertical flow of high velocity. But these conceivable side-wall paths have been anticipated in the design of the methods. Side-wall channels are sealed off when a piezometer or tube is inserted in the soil. In the auger-hole method, vertical channels which fall partly inside the hole should not be important, as they have only the effect of making the hole inappreciably larger. Horizontal root holes were not observed in the cores at Site 1 from below the water table. The plants growing on the soil surface were hydrophytes with root systems penetrating to the water table in a generally vertical direction. No root holes were observed at Site 2.

The effect of root holes (Site 1), in line with the above reasoning, is particularly noticeable in comparing the tube measurement, 9.18 in/hr at the 18-inch depth, with the core sample values 21.4 and 39.1 in/hr at the 15- and 21-inch depths. The discrepancy between tube and core values is especially noticeable when one observes, in the tube diagram of Figure 2, that soil below the base of the tube affects the permeability more than does soil above the base of the tube. That is to say, the 39.1 core value should be the value to compare with the 9.18 tube value rather than the 21.4 value.

In one case, the measured core value was not higher than for another method: the measured core value at the depth of 14-16 inches was 21.4; the measured piezometer value at the depth of 14-18 inches, 24.4. To within the experimental error, the values 21.4 and 24.4 may be considered equal; but if the values are not equal but are as given, the higher piezometer value may be explained as being due in part to a high natural horizontal permeability of the soil which tends to balance the effect of root holes seen by the cores, and in part due to an increase of permeability with depth. An increase of permeability with depth is noted in the last two columns of Table 1. The piezometer cavities were centered one inch lower than the cores.

An important point remaining to be considered is the apparent decrease of permeability with decreasing hydraulic head which was observed in tests by the piezometer method both in the field and laboratory where many root holes were present (Fig. 4). The effect manifests itself in a non-linear curve of the relation of $\log_e h_2$ to t as shown in the upper curve of Figure 4. There are several offhand explanations, most of which are not tenable.

The effect is not likely due to an overall drawdown of the water table around the piezometer. KIRKHAM and VAN BAVEL [1948], assuming an average soil with ten per cent drainable pore space, showed that drawdown in the case of an auger hole should be negligible For a piezometer cavity, the effect should be even smaller. If an overall drawdown were the cause, the effect would occur both with and without root holes.

One might consider that the decrease in permeability with decreasing hydraulic head may be a time effect because, in the field methods, hydraulic head decreases with time. BODMAN [1937], ALLISON [1947], and others have observed decreases in soil permeability with time. They used disturbed laboratory samples and were concerned with times up to six months or more. The effect in the present case is one of minutes or hours. There is no doubt that the permeability of undisturbed soil below the water table will change with time, but the present authors have observed no significant changes in periods up to seven days, either in soils with or without root holes.

The present writers do not fully understand the effect of root holes in causing the measured permeability to decrease as a piezometer of small diameter fills. The effect has not been observed except where root holes are present. It has not been observed in the tube or auger-hole method. A plausible explanation may be sought for in the fact that root holes may act like water sources or sinks in the soil medium. These sources and sinks may empty and refill during a permeability test. In the refilling process, air may be trapped. Trapped air would tend to decrease the filling rate. Eq. (1) was developed on the basis of an homogeneous (and isotropic) soil and thus does not take into account the effects of such sources and sinks. In addition, Darcy's law, basic in the theory, does not apply to flow in large channels.

If the volume occupied by root holes in the region about a piezometer cavity is small compared to the volume of the tube or pipe below the water table, one can expect that the anomalous effect of root holes will be negligible compared with the effect of the soil as a whole. This, in fact, was observed. When piezometers of two-inch diameter were used, instead of the smaller ones, the apparent decrease of permeability with hydraulic head did not occur. Moreover, in the tube and auger-hole methods, where large cavities (eight and four inches in diameter) were used, rates of water rise agreed with the theory as closely as could be observed both in soils with and without root holes. By agreement with theory is here meant that the relation of $\log_e h_2$ to t yielded a straight line.

Conclusions--It is realized that the data here presented are not extensive, nor have the theoretical aspects of the problem been completely studied. Yet it is believed that certain tentative conclusions can be drawn concerning the methods. These conclusions are based in part on theoretical considerations and in part on the experimental data, or both.

(1) The experimental data from this study suggest that information on soil anistropy can be obtained by permeability measurements using field methods where the ratio of radius to length of inflow cavity (R/L) is varied. This possibility appears to be theoretically sound.

(2) Differences in measured permeability values obtained by the various methods in the present experiments appeared to be satisfactorily explained on the basis of soil anisotropy. In anisotropic soils, inflow cavities which are long compared to their diameters, ($R >> L$) measure essentially the horizontal permeability; whereas inflow cavities which are short compared to their diameters ($R << L$) tend to measure the vertical. The undisturbed-core method may be used to measure either the horizontal or vertical permeability, depending upon the direction in which the cores are taken.

(3) Root holes and other natural channels in the soil cause extreme variations in measured permeability values when the undisturbed-core method is used, and cause the rate of rise in small-diameter piezometers (one inch and smaller) to deviate from the theoretical. The effect of root holes in causing a deviation from the theoretical in small-diameter piezometers can be minimized to a point where the deviation becomes negligible by increasing the diameter of the piezometers. In the cases under study, root holes did not appear to cause noticeable deviations from the theoretical rates of water rise in test cavities when four-inch diameter auger holes and eight-inch diameter tubes were used.

(4) The sizes of soil samples associated with the undisturbed-core, piezometer, tube, and auger-hole methods (size of inflow cavities being as used in this study and referred to a common depth of 30 inches) are in the ratio 1, 35, 270, and 1400 respectively. The latter three values are based on the region where 80 per cent of the hydraulic head is dissipated. Variability in measured permeability values is less for methods with large samples. In the core method, variability was greatest, but not nearly as great as one might expect for a sample 1/35, 1/270, or 1/1400 as large as the other methods. Part of the variability is due to variability in the soil, and part due to the method of measurements. How much of the variation for the several methods is due to a weakness in the method itself and how much due to variability in the soil, cannot be specified.

(5) Soil cores in essentially undisturbed state are difficult to obtain from water-saturated soils below a water table. (Permeability measurements on undisturbed cores from unsaturated soils, where they are perhaps the most useful, were not a part of this study.)

(6) The piezometer method appears well suited for general use in the field because of its ability to measure permeability at practically any depth in both uniform and non-uniform soils. The auger-hole method is well adapted for measuring permeability in unstratified soils and appears particularly advantageous for soils having many root holes and other natural channels. The tube method, a special case of the piezometer method with large diameter and a cavity of zero length, should be especially useful in measuring essentially the vertical permeability in anisotropic soils.

References

ALLISON, L. E., Effect of microorganisms on permeability of soil under prolonged submergence, Soil Sci., v. 63, pp. 439-450, 1947.

BODMAN, G. B., The variability of the permeability "constant" at low hydraulic gradients during saturated water flow in soils, Soil Sci. Soc. Amer. Proc., v. 2, pp. 45-53, 1937.

CASAGRANDE, A., Seepage through dams, J. New Eng. Water Works Assoc., v. 51, pp. 131-172, 1937.

FREVERT, R. K., and D. KIRKHAM, A field method for measuring the permeability of soil below a water table, Highway Research Board Proc., v. 28, pp. 433-442, 1948.

KIRKHAM, D., Proposed method for field measurement of permeability of soil below a water table, Soil Sci. Soc. Amer., v. 10, pp. 58-68, 1945.

KIRKHAM, D., and C. H. M. VAN BAVEL, Theory of seepage into auger holes, Soil Sci. Soc. Amer. Proc., v. 13, pp. 75-82, 1948.

LUTHIN, J. N., and D. KIRKHAM, A piezometer method for measuring permeability of soil in situ below a water table, Soil Sci., v. 68, pp. 349-358, 1949.

VAN BAVEL, C. H. M., and D. KIRKHAM, Field measurement of soil permeability using auger holes, Soil Sci. Soc. Amer. Proc., v. 13, pp. 90-96, 1948.

VREEDENBURGH, C. G. J., On the steady flow of water percolating through soils with homogeneous-anisotropic permeability, International Conf. on Soil Mech. and Foundation Eng., v. 1, pp. 222-225, Harvard University, Cambridge, Massachusetts, 1936.

U. S. Regional Salinity and Rubidoux Laboratories (R.C.R.),
Riverside, California
(Work done at Iowa State College while on leave of absence)

Iowa State College (D.K.),
Ames, Iowa

(Manuscript received April 20, 1951; presented by title at the Thirty-First Annual Meeting, Washington, D. C., May 1, 1950; open for formal discussion until January 1, 1952.)

Transactions, American Geophysical Union Volume 32, Number 4 August 1951

PARAMETERS FOR RELATING UNIT HYDROGRAPHS TO WATERSHED CHARACTERISTICS

Charles Grant Edson

Abstract--It is suggested that the physical characteristics of a watershed exert two simultaneous and distinct influences upon the resultant unit hydrograph: one, whereby the runoff is brought to the valley; the other, in getting the runoff through the mouth. An empirical equation based on this thesis results in two parameters which are readily expressible in terms of the peak discharge and the time of peak. Between these two sets of parameters, the functional relationship is sufficiently complex to rob the latter set of any direct tie-in with the watershed characteristics. Herein lies a possible explanation of the general failure encountered in correlating watershed characteristics with peak discharge and time of peak. It is hoped that the proposed parameters may be more successful in bringing about this much sought-after correlation.

SHERMAN [1932] defined a unit hydrograph as the discharge-time relationship resulting from a steady effective rainfall of unit duration uniformly distributed over a watershed. The unit hydrograph is specifically restricted to surface discharge even as the so-called effective rainfall is restricted to that portion of the total rainfall which produces surface runoff. It follows, therefore, that the unit hydrograph is independent of such variables as infiltration, antecedent flow, and ground water. A typical unit hydrograph is shown in Figure 1, together with a mathematical statement of its pertinent characteristics.

If isochrones could be drawn to represent the time required for each local element of effective rainfall to reach the mouth of a watershed, the cumulation of area (A) with time (T) would result in an approximate parabola

$$A \propto T^x \qquad x > 1$$

so that the runoff discharge (Q) might become

$$Q \propto T^x \qquad x > 1 \ldots\ldots\ldots (1)$$

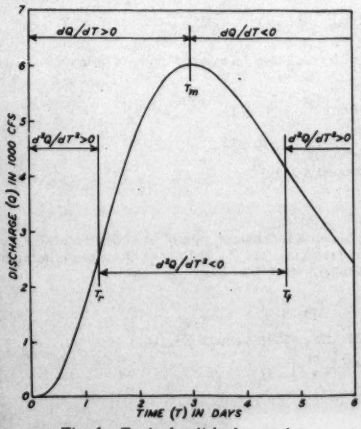


Fig. 1--Typical unit hydrograph

When runoff accrues simultaneously over all parts of a watershed, however, the time of travel required for each component is so affected by the presence of the other components that the hypothetical isochrones are invalidated. It is reasonable to regard the consequent delay in delivery as the result of valley storage. In other words, a portion of the total runoff must be stored in the valley upstream from the mouth of the watershed in order to produce the discharge. In a certain sense, therefore, the valley of the watershed acts as a reservoir, the discharge of which is known to decrease exponentially with time

$$Q \propto e^{-yT} \qquad y > 0 \ldots\ldots\ldots (2)$$

Thus the reservoir action of the valley is seen to have a damping effect on the flow implied by proportion (1). Accordingly, proportion (1) must continue in effect indefinitely. On the other hand, since valley storage must exist for even the slightest amount of discharge, proportion (2) is seen to be in effect from the very inception of runoff. The combined effect, therefore, becomes

$$Q \propto T^x e^{-yT} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

which possesses all the pertinent characteristics of the unit hydrograph shown in Figure 1. The fact that the falling leg of a unit hydrograph becomes approximately linear when plotted on semi-logarithmic paper simply means that proportion (1) is dominated by proportion (2) some time after the peak discharge. At no time prior to the peak discharge, however, is proportion (2) dominated by proportion (1) so that proportion (3) cannot be developed into an empirical equation by the usual methods of curve fitting.

On the basis of proportion (3), the following equation has been adopted for the unit hydrograph

$$Q = BT^x e^{-yT} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

where Q is the discharge in cubic feet per second corresponding to T, the time in days reckoned from the beginning of runoff; while B, x, and y are constants for the particular unit hydrograph. If the total effective rainfall in (4) be one inch and the drainage area, A, be measured in square miles, the total volume of runoff must be A inch sq mi. Since all this water is to be discharged as the unit hydrograph, it follows that

$$\int_0^\infty QdT = A \text{ inch sq mi} = CA \text{ cfs-days}$$

where C = 242/9 is the indicated conversion constant.

To facilitate the integration of (4), let x = (n - 1) and yT = z. Then

$$\int_0^\infty QdT = By^{-n} \int_0^\infty z^{n-1} e^{-z}\, dz = By^{-n}\Gamma(n) \text{ cfs-days}$$

where $\Gamma(n)$ is the gamma function of n. After appropriate substitutions, it appears that

$$B = CAy^{x+1}/\Gamma(x+1) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

whence (4) becomes

$$Q = CAy\,(yT)^x e^{-yT}/\Gamma(x+1)$$

making Q a function of the drainage area and the two parameters, x and y.

Other properties of (4) may be obtained by differentiation. Thus the value of Q must be either maximum or minimum when

$$dQ/dT = Q(x/T - y) = 0 = T^{x-1}(x - yT)e^{-yT}$$

whence

$$T = 0, \text{ provided } x > 1$$
$$T = x/y$$
$$T = \infty$$

If $x < 1$, $dQ/dT = \infty$ when $T = 0$ which is impossible with a constant rate of effective rainfall. Accordingly, $x > 1$. When the solutions to $dQ/dT = 0$ are tested in (4), it follows that Q is minimum (namely, zero) when $T = 0$ and $T = \infty$, while Q is maximum when

$$T = x/y = T_m \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

the time of maximum discharge. From the combination of (4) through (6), it follows that

$$Q = CAy\,(x/e)^x/\Gamma(x+1) = Q_m \quad \ldots\ldots\ldots\ldots\ldots\ldots (7)$$

the maximum discharge.

Similarly, the value of dQ dT must be either maximum or minimum when

$$d^2Q/dT^2 = 0 = (x - yT)^2 - x$$

whence

$$T = (x \pm x^{0.5})/y$$

When these solutions are tested it follows that

$$T = (x - x^{0.5})/y = T_r \quad \ldots\ldots (8)$$

$$T = (x + x^{0.5})/y = T_f \quad \ldots\ldots (9)$$

the time of maximum and minimum dQ/dT, respectively.

Term A may now be eliminated from the above equations by defining the discharge in cubic feet per second per square mile of drainage area as

$$q = Q/A$$

whence (4) and (7) become

$$q = Cy(yT)^x e^{-yT}/\Gamma(x+1) \quad \ldots\ldots (10)$$

$$q_m = Cy(x/e)^x/\Gamma(x+1) \quad \ldots\ldots (11)$$

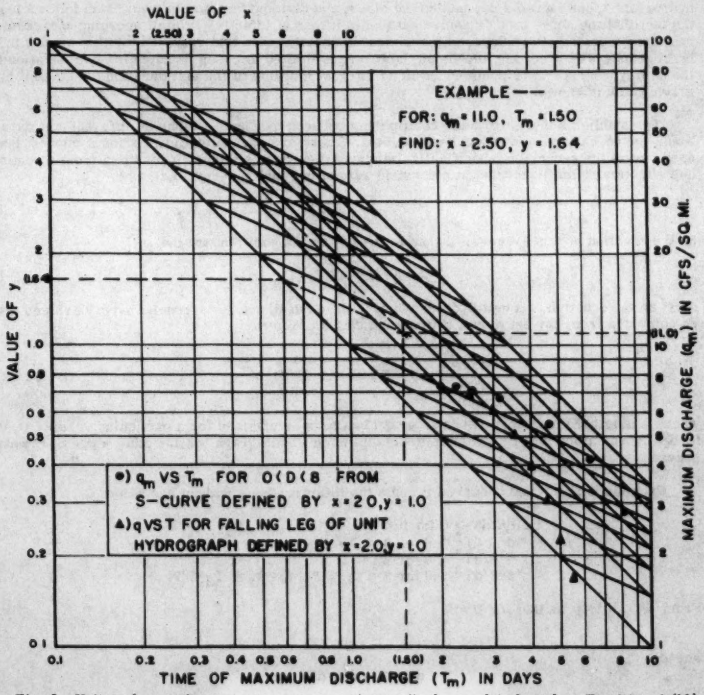

VALUE OF x
1
2 (2.50) 3
4
5
6
8
10
EXAMPLE——
FOR: q_m = 11.0, T_m = 1.50
FIND: x = 2.50, y = 1.64
VALUE OF y
MAXIMUM DISCHARGE (q_m) IN CFS/SQ MI.
●) q_m VS T_m FOR 0<D<8 FROM S-CURVE DEFINED BY x=2.0, y=1.0
▲) q VS T FOR FALLING LEG OF UNIT HYDROGRAPH DEFINED BY x=2.0, y=1.0
TIME OF MAXIMUM DISCHARGE (T_m) IN DAYS

Fig. 2--Unit-hydrograph constants versus maximum discharge data based on Eq. (6) and (11)

so that the characteristics of any unit hydrograph are completely defined by the values of x and y.

Since in any given unit hydrograph q_m and T_m are known, the corresponding values of x and y may be determined from (6) and (11). The computation, however, is more readily handled by graphical methods as indicated in Figure 2. From a combination of (6) and (11), it appears that

$$q_m T_m = Cx(x/e)^x/\Gamma(x+1) = C(x/e)^x/\Gamma(x) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (12)$$

where for a constant value of x the product $q_m T_m$ defines an hyperbola. If T_m be plotted against q_m on full logarithmic paper, the lines of constant x reduce to a family of straight lines all having a negative slope of unity. The lines of constant y are then determined directly from (6). In the resulting grid system, the y = 10 line serves as an approximate scale for x while the x = 1 line does the same for y.

It is necessary at this time to consider the unit duration of the effective rainfall. According to the basic unit-hydrograph theory, the discharge ordinates resulting from different amounts of effective rainfall are directly proportional to those amounts provided there be no difference in the unit duration. For example, the discharge ordinates resulting from two inches of effective rainfall accruing in one day are said to be twice those produced by one inch of effective rainfall in the same period. Although this statement can be shown to be erroneous, it is sufficiently accurate for engineering practice. To illustrate a further ramification of the theory, let the total amount of effective rainfall be one inch and let the unit duration, D, be measured in days. Then a two-day unit hydrograph (D = 2) may be determined for a one-day unit hydrograph by adding two one-day unit hydrographs, one lagged a day behind the other, and dividing the total by two. This follows from the fact that the above total is equivalent to two inches of effective rainfall accruing at a constant rate over a period of two days, which amount is exactly twice that required for the two-day unit hydrograph. The preceding technique, however, is limited to cases in which the unit duration for the unit hydrograph to be synthesized is an integral multiple of the unit duration for the unit hydrograph which is known.

To establish a more workable relationship between unit hydrographs of different unit durations, the so-called s-curve has been devised. There are several definitions for s-curves, but as used herein the s-curve is specifically the discharge-time relationship resulting from a continuous effective rainfall accruing at a constant rate of one inch per day. Let

$$S = F(T) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (13)$$

be the equation of this s-curve. It then follows from the basic theory that

$$Q = [F(T) - F(T - D)]/D \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (14)$$

must be the equation of a unit hydrograph of D-days durations. Conversely, s-curve values may be computed from any set of unit hydrograph data as follows

$$S = F(nD) = D \sum_{n=0}^{n=n} Q_n \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (15)$$

where n is integral. Once a unit hydrograph has been determined for a particular value of D, the foregoing equations make it possible to obtain the unit hydrograph for any other value of D whatsoever.

Examination of actual s-curves reveals the following facts without exception

$$dS/dT > 0 \text{ for } 0 < T$$
$$d^2S/dT^2 > 0 \text{ for } 0 < T < T_2$$
$$d^2S/dT^2 < 0 \text{ for } T_2 < T$$
$$d^3S/dT^3 > 0 \text{ for } T < T_1 \leq T_2, \text{ for } T_2 \leq T_3 < T$$

From (14), it follows that for D = 0

$$Q = dS/dT$$

whence

$$dQ/dT = d^2S/dT^2, \text{ etc.}$$

Table 1--Data obtained from s-curve defined by Eq. (16)

D	T_m	q_m	x	y	b	T_r
day	day	cfs/sq mi				day
0.0	2.00	7.29	2.00	1.000	13.4	0.586
0.5	2.26	7.30	2.50	1.105	11.5	0.832
1.0	2.54	7.14	3.00	1.180	8.70	1.075
2.0	3.16	6.74	4.03	1.275	3.78	1.584
4.0	4.62	5.50	5.67	1.225	0.266	2.68
6.0	6.32	4.20	6.20	0.980	0.022	3.79
8.0	8.14	2.80	4.50	0.553	0.020	4.31

Table 2--Comparison of s-curves obtained from different unit durations

T	D = 0.5 day		D = 1.0 day	
	q	s	q	s
day	cfs/sq mi	cfs/sq mi	cfs/sq mi	cfs/sq mi
0.0	0.00	0.00	0.00	0.00
0.5	1.18	0.59	0.60	0.60
1.0	3.80	2.49	2.68	2.68
1.5	6.04	5.51	5.00	5.60
2.0	7.14	9.08	6.58	9.26
2.5	7.19	12.68	7.12	12.72
3.0	6.48	15.92	6.81	16.07
3.5	5.52	18.68	6.00	18.72
4.0	4.43	20.90	4.97	21.04
4.5	3.44	22.62	3.92	22.64
5.0	2.55	23.90	2.98	24.02
5.5	1.87	24.84	2.20	24.84
6.0	1.34	25.51	1.58	25.60

From (6), (8), and (9) respectively

$$T_m = x/y = T_2$$
$$T_r = (x - x^{0.5})/y = T_1$$
$$T_f = (x + x^{0.5})/y = T_3$$

Now if $T_1 = T_2 = T_3$, it follows that

$$x = 0 = T_m$$

which is impossible since $x \not< 1$. Therefore, $T_1 < T_2 < T_3$.

The preceding discussion on s-curves suggests a method for checking (4) against the basic unit-hydrograph theory. As an example, let x = 2 and y = 1 define a unit hydrograph for D = 0. It follows from (15) that the s-curve for D = 0 is defined by the integral of (4)

$$\int_0^T Q dt = [CA/\Gamma(3)] \int_0^T T^2 e^{-T} dT$$

$$F(T) = CA\,[1 - 0.5\,T^2 e^{-T} - e^{-T}(T+1)] \quad (16)$$

while from (14) the unit hydrograph for any D > 0 becomes

$$Q = [(CA/D)e^{-T}]\left\{0.5\,[e^D(T-D)^2 - T^2] + e^D(T-D) - T + e^D - 1\right\} \quad \ldots (17)$$

For $Q = Q_m$ in (17), $dQ/dT = 0$, whence

$$T = D/(1 - e^{-0.5D}) = T_m \quad \ldots (18)$$

for which

$$Q/A = [(C/D)e^{-T_m}]\,[(T_m + 1)(e^D - 1) - De^D] = q_m \quad \ldots (19)$$

Table 1 is then computed from (18), (19), (12), (6), (5), and (8) with the results plotted as circles on Figure 2. It will be noted that all symbols reduce to the lower case form when divided by A; for example, B/A = b, S/A = s.

The inter-relationship between the basic unit hydrograph theory and the theory implied in (4) may now be tested by comparing two or more independent determinations of an s-curve on the basis of data obtained from Table 1. For the purpose of illustration, unit hydrographs have been computed for D = 0.5 and D = 1.0; and from these, s-curves have been obtained by use of (15). The results are shown in Table 2. It will be noted that while the agreement between the two s-curves is good it is not quite perfect. For s-curves obtained from still larger values of D, the discrepancy undoubtedly would be even more pronounced. Just how much of this discrepancy should be charged to each theory is at present a moot question. For a small change in D, however, it would appear that (4) is in substantial agreement with the basic unit hydrograph theory.

Conclusions--It should not be inferred that (4) represents any improvement over unit hydrographs obtained in the conventional manner. Quite clearly, it does not. In the empirical field, however, where attempts are made to establish relationships between unit hydrographs and watershed characteristics, it is felt that the parameters of (4) may be of considerable value. The fact that q_m and T_m are functions of x and y makes their relationship to the watershed so complex that direct correlations are usually doomed to failure. Were the watershed characteristics related directly to x and y, it is felt that this complexity would be eliminated. Because of the involved effect of unit duration, however, it is recommended that a common value of D be adopted for all unit hydrographs under consideration, required conversions being accomplished by the use of S-curves. The values of q_m and T_m may then be converted to values of x and y by means of Figure 2.

Reference

SHERMAN, L. K., Streamflow from rainfall by unit-graph methods, Eng. News Rec., v. 108, no. 14, pp. 501-505, April 7, 1932.

Engineering and Industrial Experiment Station,
University of Florida,
Gainesville, Florida

(Communicated manuscript received July 14, 1950;
open for formal discussion until January 1, 1952.)

Transactions, American Geophysical Union Volume 32, Number 4 August 1951

EVALUATION OF TWO ELEMENTS AFFECTING THE CHARACTERISTICS OF THE RECESSION CURVE

Carroll F. Merriam

Abstract--This is an entirely empirical approach to the problem of evaluating two factors which play dominant parts in determining the shape which the runoff recession curve would take if we assumed no subsequent rainfall. One of these is the depletion of ground-water storage and the other the draining away of that portion of the runoff which behaves as though it never enters the ground. The two apparently influence the actual recession curve independently of each other so that, by knowing the characteristics of each, the combined effect may be predicted. The application of envelope curves is demonstrated for the purpose of elimination of variables which may be considered statistically to approach zero as a limit.

If the porosity of the soil and the area of the aquifer were known, it would merely be a matter of arithmetic to determine the relationship between water-table elevation and volume of ground water. However, when neither the area nor the porosity can even be wildly guessed, the problem requires an entirely different approach. Such is the situation in the Susquehanna Valley; the percentage of the entire 27,000 sq mi of area where the water table presents a free surface is not even vaguely known while the porosity may vary from that of fractured crystalline rock to loose glacial drift.

A quantitative determination of the amount of ground water released with given drop in average elevation and also knowledge of the recession characteristics of water "in transit" are essential to the success of predictions of assured flow previously reported by MERRIAM [Trans. Amer. Geophys. Union, pp. 384-386, 1948]. The results indicate that at least some success was obtained. Inasmuch as prior to this time an exposition of the method has been presented only informally at a round-table discussion before the Section of Hydrology, and never in writing, it seems desirable to explain the basic principles used in reaching a solution.

The essence is that stream flow is used as a measure of the amount of water actually drained from underground sources during the time that the drop in the ground-water index is carefully measured by weekly observations. Obviously there would at best be only very rare instances, if any, when this could be done without risk of error arising from additional precipitation. It might be possible to select outstanding periods of particularly severe drought in the hope that the effect of residual percolation would be small, but in a humid region like the eastern part of the United States there would be no assurance of success.

Fortunately the effects of percolation and direct drainage of surface water would cause errors always in the same direction. Not only will the drop in ground-water index in a given period of time be reduced, but the quantity of river flow per foot of drop would appear to be greater. With this in mind, all of the data may be used and the points plotted as scatter diagrams, but since errors are all in the same direction and the values can be assumed statistically to approach zero as a limit, the purpose is not to draw the most representative curve through the points but rather to establish the envelope, or limit, of an "inhibited zone." As will be seen in Figures 1 and 2, the scattered points do have a more or less definite fringe beyond which no points appear. The limits could then be considered the true functions sought under the condition that there would be no addition to ground-water storage and no increase in stream flow because of rain during the period when measurements are made.

In Figure 1, the envelope curve represents the quantity of water in terms of thousands of cfs-days per foot of change in ground-water elevation expressed as a function of the ground-water index or elevation in feet. (For description of the development of the ground-water index, in effect the reduction of data from wells having widely different characteristics to one common denominator, the dimension of which is feet, see MERRIAM [Trans. Amer. Geophys. Union, v. 24, pp. 598-603, 1942].) The units of the scale of abscissae are somewhat unusual but follow logically from the fact that the flow is measured in thousands of cfs for a period of days, and then divided by the drop in ground-water elevation in feet. By cancellation

$$(ft^3/sec) \times (sec/day) \times (day/ft) = ft^2$$

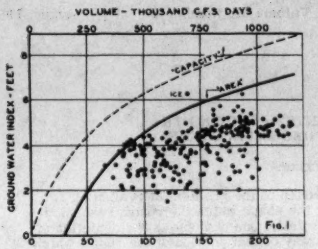


Fig. 1--Relation of elevation to volume of ground-water flow

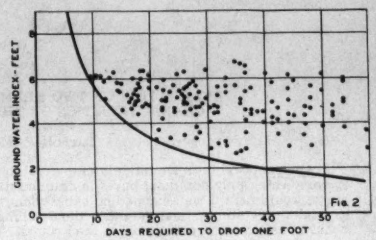


Fig. 2--Relation of elevation to drop in ground-water level

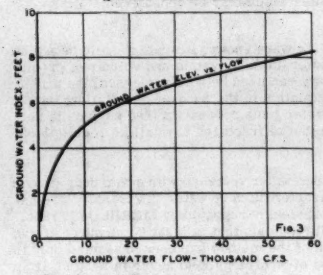


Fig. 3--Relation of elevation to rate of ground-water flow

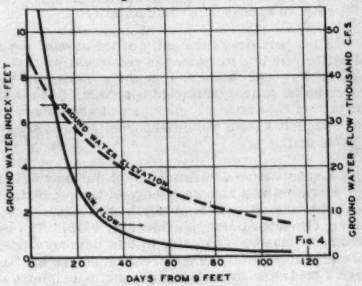


Fig. 4--Time-elevation relationship

and so it will be seen that the dimension of the unit is square feet. As far as can be seen at present, ground water behaves as though stored in a lake having a free water surface, the fluctuations of which are expressed by the ground-water index. The envelope curve would correspond to the customary one showing the area of the lake in square feet at various elevations.

If we integrate the "area" curve on Figure 1 with respect to elevation, the result is the volume curve shown in dash line. This is similar to the "capacity" of a reservoir, and is referred to the upper horizontal scale. It should be remarked that the total volume between the mean maximum elevation in spring and the mean minimum elevation in fall is only 430,000 cfs-days, or approximately three per cent of the average annual flow of the river. Consequently it is obvious that considering the Susquehanna basin as a whole, ground water cannot exert a marked effect in decreasing the severity of floods. It is quite probable, on the other hand, that in a portion of the basin which is generally underlain with glacial drift, ground water may locally play a far greater role in influencing the hydrograph.

Another important characteristic of this imaginary lake, which may be assumed to be equivalent to the aggregate of all of the ground-water storage, is that the rate of discharge is just as though there were a controlled outlet, so that the flow is solely a function of the elevation of the water surface. Consequently if we now combine the envelope curves on Figures 1 and 2 by dividing for each elevation the cfs-days per foot (Fig. 1) by days per foot (Fig. 2), the result is the rate of flow as a function of ground-water elevation (Fig. 3).

Thus we have reduced ground-water storage not only to terms of an equivalent surface reservoir with known area and volume curves (Fig. 1), but have established the rating of the outlet (Fig. 3). The next task is to develop the resulting hydrograph.

This is accomplished by first integrating Figure 2 with respect to elevation, thus giving on Figure 4 the dash curve referred to the left-hand scale. This is the summation of days from an arbitrary zero, when the elevation was nine feet, for the index to drop to any given value shown on the scale of abscissae. As already brought out, the flow is solely a function of the index; consequently we can transfer by means of Figure 3 the ordinates of the dash curve to the solid curve, referred to the right-hand scale. This is the ground-water hydrograph used in connection with the forecasting of the assured flow.

As previously mentioned, the other element to be considered is the rate of decline of that portion of the total flow which may reach the river system directly without ever entering ground-water storage at all. Since the actual hydrograph is the resultant of the two components, either of which may for practical purposes be assumed to approach zero as a limit, we could evaluate the one with which we are now concerned by finding for any given value of flow the maximum rate at which the actual hydrograph had ever receded. Thus we have another application of the envelope-curve principle.

Log-log paper was used for plotting the flow for each day as a function of the flow for the day preceding, neglecting of course all days when the flow exceeded that of the day before. The points showed considerable scatter because of the many factors including depletion of ground-water storage which would prevent the drop from attaining the maximum rate. Fortunately there was a wealth of excellent data because the flow had been measured daily for a considerable period of time. In fact, the record was sufficiently long so that it could be divided into three distinct periods and treated separately to make sure that each group gave consistently the same final result. Another variation was to plot the flows for two and even three days apart, thus taking advantage of the greater drop in flow, but with some loss of definition in determining the envelope because of fewer data. Nevertheless, the results compared favorably regardless of the number of days.

A few points did fall well below the envelope, but on investigation it was found that these were caused either by sudden freeze-up of the river in winter, or by unusually rapid falling off of the flow following local storms in summer. The other points, well over 2000 in all, fell within a very definite limit. By integrating the rate of drop as expressed by difference between the logs of the flows as a function of flow, it was possible to establish very satisfactorily the hydrograph of the decline of this component without additional precipitation or influence of ground water.

By thus knowing the recession characteristics of the two components which make up the total flow, it is possible to predict their future values 7, 14, and 21 days later, and then recombine them to estimate the total flow which on those days can be counted upon at least to be equalled and in all probability exceeded.

It must be admitted that, in addition to the two factors considered in this communication, there are many others such as seasonal variations in plant use, human and industrial consumption, evaporation, and channel storage. On smaller streams and in drainage basins having a great many lakes and exposed water surface, these latter may possibly exert a controlling influence, and thus render inapplicable the method of predicting "assured flow" herein outlined.

On the Susquehanna the consumptive use is relatively unimportant compared to the total volume of flow. It is strange, however, that seasonal variations in plant use and evaporation do not, as far as can be seen at present, detract from the value of these predictions. The explanation appears to be that we are dealing primarily with water which has for the most part "escaped" capture by plant life, and is draining away through channels without enough free water surface to subject it to serious loss from evaporation.

Depletion of bank storage is undoubtedly the major part of the second factor discussed above. The rate of recession of the water "in transit" has been treated as though it were solely a function of flow, and it has been observed that both in summer and in winter this rate, approximately 20 pct per day, is so nearly the same that no distinction has yet been found.

It is also possible that when the factors having prime importance have been evaluated and accounted for, the residuals may lead to further investigation regarding those which have necessarily been neglected.

As for the influence of consumptive use on the observation wells themselves, great care is exercised to make sure that none of these is affected appreciably by over-pumping in the vicinity, and that they consequently faithfully reflect the natural fluctuations in the undisturbed water table.

While these methods do not attain a high degree of precision as compared with some other types of scientific measurement, from the practical standpoint the basic relations which were so established have proved useful. It is possible that the use of the envelope curves may have other applications in hydrologic studies where unknown errors are all in one direction and can be assumed to vary statistically, approaching zero as a limit.

Pennsylvania Water and Power Company,
Baltimore 3, Maryland

(Communicated manuscript received January 5, 1951;
open for formal discussion until January 1, 1952.)

Transactions, American Geophysical Union Volume 32, Number 4 August 1951

GEODETIC WORK EXECUTED IN MEXICO FROM APRIL 1949 TO MARCH 1950

Manuel Medina Peralta

(Translated by Maria Perri)

Geodetic triangulation--The activities in this field of operations are concentrated in three arcs of triangulation, one which is being extended along the 101st meridian, one projected in the States of Oaxaca and Chiapas to the Guatemalan border, and one along the 103rd meridian in its tie with the 26th parallel. The respective diagrams for these triangulations have been published in previous reports [MEDINA, 1950, and earlier reports], and I am therefore going to limit my discussion to the progress on the stations affected in each of the arcs.

Along the 101st meridian there was work at the stations Encantada, Jabalí, Candela, La Popa, La Lipa, Barreta, La Leona, Astillero, Pedregoso, Tanque de López, Cerro Colorado, Barrote del 31, and Fraile.

The most northern side of this arc is Barrote del 31 - Barreta, less than 20 km from the Rio Bravo del Norte (Rio Grande), and for this reason it was selected as the best length at which to connect to the triangulation of the U. S. Coast and Geodetic Survey.

The figure selected for this tie was a quadrilateral formed by the vertices: Barrote del 31 and Barreta in Mexican Territory, and Feely and Kelly together with the complementary station Dobkins in the United States, as shown in Figure 1.

The angle observations were made simultaneously on January 24-25, 1950, by observers Víctor Juárez Parra of Mexico and L. M. Chase and E. Howes of the United States. The respective chiefs of field parties were Maurilio Nava for Mexico and Curtis Le Fever for the United States.

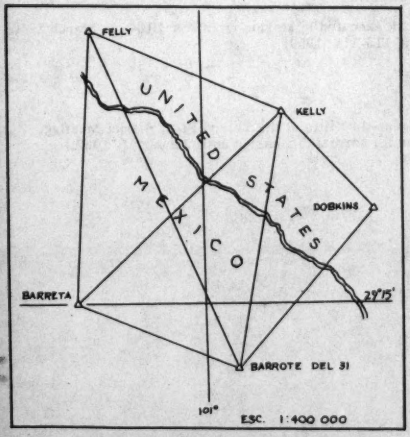


Fig. 1--Sketch of the connecting figure of the Mexican and North American triangulation at the border of both countries and in the vicinity of the 101st meridian

When the observations were completed, the necessary field computations were made and the resulting values were exchanged in order to obtain the corresponding angular and linear closures. These met the precise specifications required for geodetic operations of both Mexico and the United States.

The computational results obtained by this office are: Barreta, lat. 29°15′ 39″.772, long. 101°09′ 53″.051, altitude 527.6 m; Barrote del 31, lat. 29°11′ 10″.023, long. 100°58′ 42″.340, altitude 398.6 m; azimuth, Barreta-Barrote 31, 294°35′ 02″.31; azimuth, Barrote 31-Barreta, 114°40′ 29″.76. The logarithmic distance, Barreta - Barrote 31, is 4.2994608 Mexican datum and 4.2994650 North American datum, giving a difference of 0.0000042, which equals 0.19 m, and a precision of 1:104,884.

Along the Oaxaca and Chiapas arc, there was work at the stations Palmarillo, Potrero, Ciénega, Bandera, Piedra Blanca, Cerro Grande, Cerro Pelón, Yucuyacua, Palmar, San Felipe, Guialana, and San Felipe.

Along the 103rd meridian, the work was at the stations Pico de Teyra, Bancos,

Chorreado, Pico del Carpintero, and San Julián. For these observations the high-precision Wild T3 theodolite was used exclusively with the minimum of 16 directions.

Astronomic positions--LaPlace observations were made at the geodetic stations Monte Albán, Oaxaca, and the north end of the Tehuantepec Base. For longitude, time signals were received from station NSS, and the Repsold Altazimuth No. 2 was used for making observations of meridian passage of stars for time. The Horrebow Talcott method was used for latitude measurements. For azimuth determination, Polaris was observed.

Precise leveling--A precise level line was run from the south end of the Tapachula Base, at the bench mark Talismán, located on the international bridge at the Mexican-Guatemalan border, with an approximate extension of 45 km. An elevation of zero was assumed whilst a tide gage to refer this leveling to mean sea level is to be established in Puerto Madero in the vicinity of the north end of the base. This leveling was done with a high-precision Wild N III level with invar rods, on which direct readings are made to the nearest 0.01 mm.

Gravimetry--With the cooperation of N. C. Harding of the Department of Geology of the University of Wisconsin, a gravimetric profile was run from the Atlantic to the Pacific, between the ports of Tuxpan, Vera Cruz, and Acapulco, Guerrero, and passing through Mexico City. The Worden gravimeter was used. Many of the stations occupied, especially those on the Mexico-Tuxpan highway, were previously observed by Petróleos Mexicanos.

Cartography--The charts and maps edited by this office during the period covered by this report are as follows:

General Map of the State of Puebla; polyconic projection; dimensions between margins 1.62 × 1.17 m; contour interval, 200 m; graphic scale; July 1949, test reprint.

Preliminary Map of the State of Jalisco; projection, Lambert orthomorphic, standard parallels 17° and 30°; dimensions, 0.945 × 0.88 m; contour interval, 300 m; scale, 1:500,000; September 1949.

Geographic Map of the State of Zacatecas; polyconic projection; dimensions, 0.87 × 0.735 m; contour interval, 150 m; scale, 1:500,000; December 1949.

State of Chihuahua; polyconic projection; dimensions, 1.755 × 1.52 m; contour interval, 300 m; scale, 1:400,000; February 1949.

Reference

MEDINA PERALTA, MANUEL, Geodetic work executed in Mexico from April 1948 to March 1949, Trans. Amer. Geophys. Union, v. 31, pp. 115-118, 1950.

Oficina de Geografía,
Tacubaya, D. F., Mexico

(Manuscript received May 15, 1950; presented by title at the Thirty-First Annual Meeting, Washington, D. C., May 1, 1950; open for formal discussion until January 1, 1952.)

Transactions, American Geophysical Union Volume 32, Number 4 August 1951

DISCUSSION OF

"VEDERNIKOV'S CRITERION FOR ULTRA-RAPID FLOW"

by RALPH W. POWELL

[Trans., v. 29, pp. 882-886, 1948]

V. V Vedernikov (Moscow, U.S.S.R., translated by Mrs. Justina Epp from C.-R. Acad. Sci., v. 69, pp. 507-510, 1949; notation changed by the editor to conform to that of Powell)--The parameter β, entering into the expression of the criterion (2), is not always interpreted exactly. For a uniform flow it has the form [VEDERNIKOV, 1946]

$$\underline{V} = (1 + \beta)\, MV/p\,(u - V) \qquad (16)$$

The calculations performed by Powell for criterion (1) are not all correct. We consider it necessary to dwell on the determination of parameter β and the values of the criterion.

In derivation of the formula for the criterion from the equations for unsteady motion, one can calculate the hydraulic slope by the Chezy formula

$$I = V^2/C^2\, R \qquad (17)$$

Then for the turbulent flow in channels with walls not completely rough the Chezy coefficient C is a function of the Reynolds number, or one can present the gradient for such channels in the form of a power relationship

$$I = A\, V^p/R^{1+\beta} \qquad (18)$$

(in which p = 2 for channels with completely rough walls). Powell considers that the sum of exponents in the last equation must always equal $p + 1 + \beta = 3$, or that $p = 2 - \beta$, and correspondingly, erroneously maintains that for the flow in a channel with completely rough walls, from contemporary semi-empirical formulas, it follows that $\beta = 0$, inasmuch as p = 2.

As can be seen from equations (15) and (16) of VEDERNIKOV [1945] and equations (3) and (5) of VEDERNIKOV [1946; see also VEDERNIKOV, 1947], the value β, entering into the expression of criterion (1), and of criterion (6) in VEDERNIKOV [1946], appears when taking the derivative of C^2R along s (that is, lengthwise of the wave) and has a value corresponding to the value of this derivative at the point of the wave. Hereby

$$\partial(C^2R)/\partial s = [\partial(C^2R)/\partial F]\, \partial F/\partial s \qquad (19)$$

that is, the derivative of C^2R along the area of the live cross-section F enters into the calculation. Taking this derivative we get

$$\partial(C^2R)/\partial F = C^2\,[1 + (2\,R/C)\,\partial C/\partial R]\,\partial R/\partial F = C^2\,(1 + \beta)\,\partial R/\partial F \qquad (20)$$

It was here that the designation

$$\beta = (2\,R/C)\,\partial C/\partial R \qquad (21)$$

was introduced.

But if we use (18) instead of $\partial(C^2R)/\partial F$ we shall have $\partial(R^{1+\beta})/A\partial F$ and $(1 + \beta)$ will stand alone in parentheses. Hereby $\partial R/\partial F = M/\chi$ [VEDERNIKOV, 1945, 1947].

Contemporary semi-empirical formulas for channels with completely rough walls have the form $C = a \log (R/k) + b$. Here k is the effective height of the roughness. Disregarding the dependence of b on the form of the channel (Keulegan considers this dependence probable), we find

$$\beta = a/1.15\ C \quad (22)$$

For smooth channels, according to Lee (corresponding to the Blasius Law), $I = A\,V^{1.75}/R^{1.25}$, we have $p = 1.75$ and $\beta = 0.25$. But this formula has a definite limit of applicability. If one takes $p = 2.0$ for channels with smooth walls, according to contemporary practice, that is, if one uses (17), then C will be a function of the Reynolds number. We can write

$$\partial C/\partial R = (\partial C/\partial \underline{R})\,\partial \underline{R}/\partial R = (\partial C/\partial \underline{R})\,[4\,V/\nu + (4\,R/\nu)\,\partial V/\partial R] = (\underline{R}/R)\,(1 + R\partial V/V\partial V)\,\partial C/\partial \underline{R} \quad (23)$$

We notate

$$\beta_0 = (2\,\underline{R}/C)\,\partial C/\partial \underline{R} \quad (24)$$

Then

$$\beta = (2\,R/C)\,\partial C/\partial R = (2\,\underline{R}/C)\,(\partial C/\partial \underline{R})\,[1 + (R/V)\,\partial V/\partial R] = \beta_0\,[1 + (R/V)\,\partial V/\partial R] \quad (25)$$

Along the wave $\partial V/\partial F = (u - V)/F$ and $\partial V/\partial R = (\partial V/\partial F)\,\partial F/\partial R = (u - V)/MR$ [VEDERNIKOV, 1947].

At the point of the front of the wave which disturbs the uniform motion, $u = u_0$, $V = V_0$, $M = M_0$, and $R = R_0$ [VEDERNIKOV, 1947, p. 68]. Consequently

$$\beta = \beta_0 + \beta_0\,(u_0 - V_0)/M\,V_0 \quad (26)$$

$$\underline{V} = M\,(1 + \beta_0)\,V_0/2\,(u_0 - V_0) + \beta_0/2 \quad (27)$$

But since for the evaluation of the character of the flow $\underline{V} \gtrless 1$, we can write $M_0\,(1 + \beta_0)\,V_0/2\,(u_0 - V_0) \gtrless 1 - \beta_0/2$ instead of (27), and the criterion for the evaluation of the character of the flow in channels with smooth walls takes the form

$$V_0 = M\,(1 + \beta_0)\,V_0/(2 - \beta_0)\,(u_0 - V_0) \gtrless 1 \quad (28)$$

The result (28) is equivalent to the result obtained when the semi-empirical formula for the Chezy coefficient C is exchanged on a small section with formula $C^2 = A'_R\,(R)^{\beta_0}$ with the help of (24). Then the Chezy formula takes on the form of (18)

$$I = (1/A'_R)\,V^{2-\beta_0}\,\nu^{\beta_0}/(4\,R)^{\beta_0}\,R = A\,V^{2-\beta_0}/R^{1+\beta_0} = A\,V_0^{\,p}/R^{1+\beta_0} \quad (29)$$

where $p = 2 - \beta_0$, and β_0 is calculated from (24). It is of importance that such a substitution shows that in the empirical formulas of Lee, Freeman, and others the value of A must generally depend on the viscosity of the fluid.

For channels with smooth walls the semi-empirical formulas have the form $C = a' \log (\underline{R}/C) + b'$. Disregarding the dependence of b' on the form of the channel, we find (see Powell, Eq. 11)

$$\beta_0 = (2\,\underline{R}/C)\,\partial C/\partial \underline{R} = 2\,a'/(C + a') \quad (30)$$

It is evident that on a small sector one can exchange the semi-empirical formula (for C) and for channels with smooth walls, with a dependence of the form $C^2 = C_0^2\,R^{\beta'}$. Taking the derivative of $C^2 = C_0^2\,R^{\beta'}$ with respect to R, we calculate the value β' for such an exchange according to (25), assuming for the uniform motion (but not for the wave), $\partial I/\partial R = 0$,

$$\partial V/\partial R = \partial C\sqrt{R\,I}/\partial R = \sqrt{R\,I}\,\partial C/\partial R + C\sqrt{I}/2\sqrt{R} = (V/C)\,\partial C/C\partial R + V/2\,R$$

Then

$$\beta' = (2\,R/C)\,\partial C/\partial R = 3\,\underline{R}\,(\partial C/\partial \underline{R})/[1 - (\underline{R}/C)\,\partial C/\partial \underline{R}] \quad (31)$$

and then for the semi-empirical formulas

$$\beta' = 1.3\,a'/C \quad (32)$$

Table 2--Values of the Froude number and the Vedernikov number

Non-wavy flow			Wavy flow			
No. of exper.	F	V	No. of exper.	F in exper.	V according to Powell	V corrected
23-1	1.69	0.90	8-12	2.49	1.09	1.41[a]
23-2	1.67	0.83	8-13	2.60	1.10	1.32
23-3	1.61	0.71	8-14	2.62	1.09	1.28
.....	.....	.....	8-15	2.54	1.05	1.26
.....	.....	.....	8-16	2.58	1.04	1.26
.....	.....	.....	8-17	2.59	1.02	1.23

[a] It must be noted that the problem can also be posed thus: To find the hydraulic elements of the channel when a non-wavy flow of the same quantity as given in the experiment, is possible. Then, not only a different velocity of flow, but also a different depth of filling of the given channel would occur. In VEDERNIKOV [1946], performing the calculation of such a non-wavy flow for experiment 8-12, we obtained for it $\underline{V} \approx 1.26$.

From this at unit values of a and a′ follows the essential conclusion, that at equal values of C the value of β' at uniform motion is $1.3 \times 1.15 \approx 1.5$ times larger for channels with smooth walls than β for channels with rough walls. It is natural that by substitution of value β' in (32), Eq. (16) gives the same numerical result as (28) for value β_0 in (30). However, at equal values of R the value β will be larger for channels with rough walls. Investigation of the equations of VEDERNIKOV [1945] shows that the formulas for the calculation of the values β given here are true also for the non-uniform motion (formulas (5) and (6) in VEDERNIKOV [1946]) at substitution of values u, V, M, C, F, and B in (22), (26) for the given live cross-section.

We do not give here the numerical values of a, b, and a′, b′, since there are important divergencies between the values of these magnitudes in the experiments by Zegzhda and Powell which need experimental checking of these values.

Our calculations have shown that Powell's experiments 24-2 to 24-6 and 23-1 to 23-6 in Table 1 give the values for C with an exactness quite sufficient for practical calculations; they differ little from the values C_{Bl} in the formula of Blasius. The experiments by Powell give

$$C = 1.02\, C_{Bl} = 1.02 \sqrt{8\, g/0.316}\ \sqrt[8]{R} \quad \ldots\ldots\ldots\ldots\ldots\ldots (33)$$

That a correction factor for rectangular channels is possible in the Powell experiments is due to the fact that the transition from round pipes to such channels does not reflect sufficiently the influence of the form of the channel by replacing the diameter of the pipe in the Reynolds number with four times the hydraulic radius.

Applying (25) we find the value $\beta = 0.25$, and of the criterion (28)

$$\underline{V} = M\, V/1.4\, (u - V) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (34)$$

It is noted that Powell, in his table, calculates the criterion for those experiments for which our criterion is larger than unity based on the hydraulic elements of these experiments and on the observed velocity of the flow. This may give a certain evaluation of the state of the flow. But in the experiments, for which the value of the criterion is larger than one, the flow was ultra-rapid or wavy. Powell gives an evaluation of the possibility of a non-wavy flow on the basis of the derivation of the criterion itself, and the derivation is based on the equations and the law of resistance of the non-wavy flow. Therefore, when making the calculation, he should have substituted, in the formula for the criterion, the velocity of the flow at the observed hydraulic elements, which would exist in the possible non-wavy flow, and which can be calculated from the formulas for the non-wavy flow. In Table 2 we show the values of our criterion for experiments 23-1 to 23-3 (at highest values of the Froude number for the pre-wavy flow) and the experiments 8-12 to 8-17 (at the lowest values of the Froude number for the ultra-rapid flow), according to the calculations by Powell and according to ours using (34) taking into account what has been said above. For the determination of the velocity of the non-wavy flow in 8-12 to 8-17 we use (33).

Powell calculates the non-uniformity of the distribution of velocities by introducing the coefficient α as was done in VEDERNIKOV [1945], which method of calculation was based on CHRISTIANOVICH and Others [1938]. However, the latter method of calculating non-uniformities of distribution

of velocities by introducing into the St. Venant equation the factors α/g instead of $1/g$ evokes natural objections, since there should not be the same coefficient in front of the terms $V\partial V/\partial s$ and $\partial V/\partial t$ to correct them for the non-uniformity of distribution of velocities across the cross-section. Therefore, we proceed in our following work [VEDERNIKOV, 1946, 1947] from the equations of unsteady motion in the form in which they were given by St. Venant.

In practice, the calculation of the non-uniformity in the distribution of velocities goes beyond the limit of exactness of calculations, because it does not give an essential correction. One may here note that a calculation of this non-uniformity (according to Boussinesq) leads not to an increase of the numerical value of criterion (1) as it did in the calculations of Powell, but to its decrease.

References

VEDERNIKOV, V. V., C.-R., Doklady, v. 52, no. 3, 1946 (errata given in Doklady, v. 55, p. 206, 1947).

VEDERNIKOV, V. V., C.-R., Doklady, v. 48, no. 4, 1945.

VEDERNIKOV, V. V., Toleration waves of a real fluid; in a collection on non-steady motion of water current in an open channel, by V. V. Vedernikov, N. V. Mastitskŭ, M. V. Patapov, Acad. Sci., USSR, 1947.

SABANEEV, A. A., Izv. B. E. Vedeneev Scientific Research Institute of Hydrotechnology, v. 34, 1947.

CHRISTIANOVICH, S. A., and Others, New problems in mechanics of a solid medium, Acad. Sci., USSR, pp. 21-22, 1938.

Ralph W. Powell (Ohio State University, Columbus, Ohio, Author's closure)--The first point in which Vedernikov disagrees is in the value of β for rough channels. On what seemed reasonable grounds, the author had said that for rough channels β would be zero. But Vedernikov maintains that the author's Eq. (2) (in which, by the way, β was erroneously printed as B) is not the fundamental definition of β. It should be

$$\beta = (2\,R/C)\,(\partial C/\partial R) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (21)$$

Taking the resistance equation for a rough channel to be of the form

$$C = a \log_{10} (R/k) + b = a \log_{10} R - a \log_{10} k + b \quad \ldots\ldots\ldots\ldots\ldots\ldots (35)$$

we have $\partial C/\partial R = 0.4343\ a/R$, therefore

$$\beta = (2\,R/C)\,(0.4343\ a/R) = 0.8686\ a/C \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (36)$$

Using the writer's formula for rough channels [POWELL, 1950, Eq. (8)]

$$C = 42 \log_{10} (R/\epsilon) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (37)$$

this gives

$$\beta = 0.8686 \cdot 42/C = 36.5/C \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (38)$$

Obviously this is very different from the writer's assumption that β is zero. Computing $\underline{V}$ with the β given by (38) showed it to be more than 1.00 for 21 of the writer's runs on rough channels, namely, 4-1 and 2, 5-1, 6-1 and 2, 7-1, 9-1, 10-1, 11-1 to 3, 12-1 to 3, 13-1 to 3, and 14-1 to 4. None of these gave any evidence of being ultra-rapid flow, and none of them gave $\underline{V}$ over 1.00 when β was taken as zero.

Recently ESCOFFIER [1950] has proposed a graphical method of investigating the stability of channel flow. Applying this to the above data, we find that Run 14-1 would be unstable, but all the others stable. However, the writer has been unable to reduce Escoffier's equations to a form comparable to that given by Vedernikov. Obviously the matter is very much in need of further study.

In regard to smooth channels, Vedernikov seems to agree with the writer's treatment as long as the criterion is less than one but proposes a different method when it is more. He calculates the value of $\underline{V}$ by this method for runs 8-12 to 17, and obtains values varying from 1.41 to 1.23, instead of 1.10 to 1.02 as obtained by the writer. He observes that actually before the flow became "wavy," "not only a different velocity of flow, but also a different depth of filling of the given

channel would occur." He notes that in a previous article [VEDERNIKOV, 1946] he had computed Run 8-12 by this second method and obtained $\underline{V} = 1.26$ instead of 1.41 as obtained by changing the velocity only, and 1.09 as obtained by the writer.

The writer has not been able to follow the entire procedure by which these values were worked out. He has noticed one bad numerical slip, where Vedernikov's Eq. (30) is given as $\beta_0 = (2\,\underline{R}/C) \cdot \partial C/\partial \underline{R} = 2\,a'/(C + a')$ when it should have been $2\,a'/(2.303\,C + a')$. Whether this carried forward into the computation of the values given above is not clear.

To the writer it would seem that if we are interested only in a criterion which will tell us whether the flow will be ultra-rapid or not, a method which is correct for all values less than unity is sufficient, since it will determine all cases which are not ultra-rapid. If our method gives $\underline{V}$ more than one, the flow must be ultra-rapid, whether the amount by which it exceeds one is correct or not.

References

ESCOFFIER, FRANCIS F., A graphical method for investigating the stability of flow in open channels or in closed conduits flowing partly full, Trans. Amer. Geophys. Union, v. 31, no. 4, pp. 583-586, 1950.

POWELL, RALPH W., Resistance to flow in rough channels, Trans. Amer. Geophys. Union, v. 31, no. 4, pp. 575-582, 1950.

Corrigenda--The following corrections are noted in this paper as published in the Transactions in December 1948; p. 882, the B in Eq. (2) should be β; p. 882, the equation in the fourth line of the paragraph headed Development should read $C^2\,k = V^{(2-p)}\,R^p$; p. 885, the fifth column heading should have F underscored for the Froude number.

DISCUSSION OF

"RESISTANCE TO FLOW IN ROUGH CHANNELS"
by RALPH W. POWELL

[Trans., v. 31, pp. 575-582, 1950]

W. M. Owen (Department of Theoretical and Applied Mechanics, University of Illinois, Urbana, Illinois, received November 6, 1950)--Powell's paper parallels to some extent the work reported in a recent thesis carried out under the direction of H. L. Langhaar and the writer in the Department of Theoretical and Applied Mechanics of the University of Illinois [BJELLAND, 1950]. The purpose of the thesis was to evaluate by experiments on a smooth triangular open channel a dimensionless graph based on the existing graphs for pipe flow, similar to Figure 5.

The coordinates for the dimensionless graph, Figure 7, were obtained from the following result of a dimensional analysis of open channel flow at normal depth.

$$C/\sqrt{g} = V/\sqrt{gRs} = \phi\,[(R/\gamma)\sqrt{gRs},\ e/R,\ \text{shape factor}] \quad \ldots\ldots\ldots\ldots (20)$$

The effect of the shape factor was eliminated from the experimental channel by virtue of its triangular cross-section. The curves shown in Figure 7 were obtained from the pipe-flow diagram of MOODY [1944] by making use of the following equations

$$C/\sqrt{g} = V/\sqrt{gRs} = \sqrt{8/f} \quad \text{and} \quad (R/\gamma)\sqrt{gRs} = \underline{R}\sqrt{f}/4\sqrt{8} \quad \ldots\ldots\ldots\ldots (21)$$

where f is the friction factor used in Moody's diagram and $\underline{R}$ is the Reynolds number based on pipe diameter. The preceding relation between C and f is derived from Bernoulli's equation and the Darcy formula.

The work reported in this thesis is only a part of a long-range project in which it is planned to investigate the flow conditions for several roughnesses and channels of different cross-sectional shapes.

The large amount of scatter in the data in Figure 7 is believed to be caused in part by the presence of waves originating at the entrance of the channel. The channel is now being lengthened and fitted with an improved entrance section in an attempt to eliminate this condition. After these improvements are made a series of tests of the channel in the smooth condition and for several different roughnesses will be made.

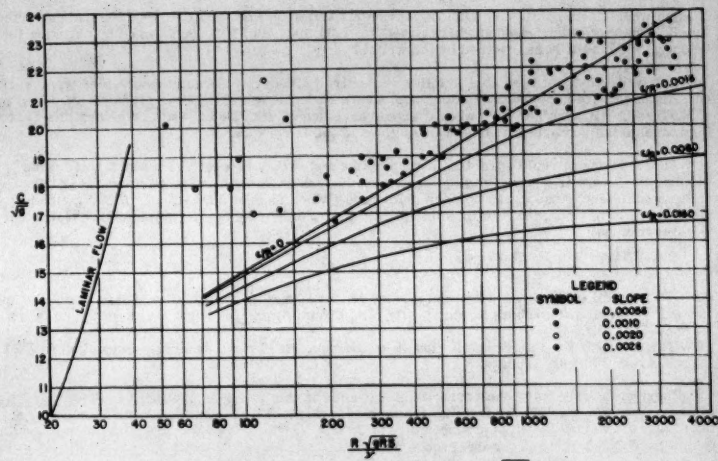


Fig. 7--Relationship of C/g to (R/)$\sqrt{gRs}$

The experimental flume consists of a forebay four feet long and four feet wide, a 90° triangular channel 40 ft long, and a tailgate. The channel was made of smooth varnished plywood supported by a rigid steel framework. The steel framework rested on several threaded posts which were used to vary the slope of the channel. Discharge measurements were made by weight. The depth of water in the channel was measured by eight point gages spaced at four-foot intervals along the channel.

Uniform flow was established for all test runs. At the higher rates of flow it was difficult to determine when uniform flow had been obtained because of the choppy appearance of the water surface. It was decided to assume that uniform flow had been obtained when the average reading of several point gages upstream was equal to the average reading of several downstream point gages.

The experimental data shown in Figure 7 appears to form a broad band which runs parallel to and slightly above the smooth pipe curve for low values of $(R/\gamma)\sqrt{gRs}$ and then crossing and falling below the smooth pipe curve for higher values of $(R/\gamma)\sqrt{gRs}$. When individual curves are drawn through the data for the different slopes, the curves fall in order increasing slope with one exception. This apparent dependency on slope was not to be expected and it is felt to be a result of the increased resistance caused by wave action at the higher velocities. Wave action may also be the cause of the band of experimental data crossing and falling below the smooth pipe curve at higher values of $(R/\gamma)\sqrt{gRs}$. However, there is no reason to expect complete agreement with Moody's data, since they apply specifically for channels of circular cross-section (that is, pipes).

The large amount of scatter of the data for values of $(R/\gamma)\sqrt{gRs} < 150$ is caused by the fact that these points lie in the transition region between laminar and turbulent flow.

In addition to the graph shown in Figure 7 the writer's data were used to make two graphs of C against R; one on log-log paper and one on semi-logarithmic paper. These graphs were made to check the following statements by Powell: "If, then, C plotted against R on log-log paper gave a straight line with a slope of one-sixth, Manning's formula would be vindicated. If, however, C is plotted against R on semi-logarithmic paper gave a straight line with a rise of 42 between R = 0.1 and R = 1, (8) would be vindicated."

The results of the writer's graphs gave a slope of 0.137 for the log-log graph and gave a rise of 36 between R = 0.1 and R = 1.0 for the semi-logarithmic graph.

Powell is to be complimented on his pioneering of this important work. It is hoped that future experiments by the writer and others will answer some of the questions raised in this paper.

References

BJELLAND, A. A., An experimental study of the flow of water through a smooth 90-degree triangular flume with variable slope, master's thesis, Univ. of Ill., 1950 (unpublished).
MOODY, LEWIS F., Friction factors for pipe flow, Trans. Amer. Soc. Mech. Engrs., v. 66, pp. 671-684, 1944.

J. Th. Thijsse (Waterloopkundig Laboratorium, Delft, The Netherlands, received December 11, 1950)--In his paper Powell has given a very valuable contribution in the struggle to end the unsatisfactory situation we have been in for too long a time.

It is 20 years since Karman, Prandtl, and others developed a theory on wall friction which is better than pure empiricism and since Nikuradse described wall roughness in terms of grain size. The laminar boundary layer with a thickness δ, more or less disturbed by wall protuberances, has become a universally accepted conception. So has the "sand roughness" k.

The difficulties involved in the transition between smooth and rough walls have been overcome to a great extent by the assumption of White and of COLEBROOK [1949] that in cases of "commercial roughness" the place of δ in the "smooth formula" and of k in the "rough formula" may be taken by the sum of both. Since Colebrook published his paper, ample evidence has been assembled to show that the "transition formula" is correct for the great majority of cases. Only where the roughness consists of an even coating of grains like sand-grains is the resistance of the wall exaggerated by the White formula, but this seldom occurs in engineering practice.

Since this fact has been recognized, we may utilize a formula which gives the relation between the shear at a wall and the velocity of the current along it as well as the increase of the velocity away from the wall. Starting from these relations a formula for the Chezy coefficient is easily found for circular cross-sections (pipes) and for wide flat canals.

A formula of this type makes superfluous the hundreds of formulas used that have no theoretical background. It is necessary to do away with these formulas, as their field of applicability is limited. Manning's formula, for instance, is only valid for rough walls and it yields wrong results if one tries to apply it in a case of transition between rough and smooth walls. Still these formulas continue in use.

If one neglects the differences between the coefficients in Keulegan's 1938 formulas 33-34 and 37-38, the approximate resistance formula

$$C = 5.75 \sqrt{g} \cdot \log (12R/k_s + 0.3\delta) \quad \ldots\ldots\ldots\ldots\ldots\ldots (22)$$

may be used for pipes as well as for flat canals.

It is no use trying to compose a more accurate (and also more intricate) formula, as it is not possible to make an accurate estimation for k [JORISSEN, 1949].

It is true that (22), which is in principle the same as Powell's Eq.(10), looks more complicated than Manning's formula. One has to realize, however, that in cases where Manning's formula (and many others) may be applied, δ is zero or negligible, which simplifies (22) considerably and reduces (10) to (8). It is easier to memorize a logarithm than a sixth root.

Of course, the logarithmic "transition" formula is not ideal. It overestimates the resistan in cases of "Nikuradse roughness." In the second place, there are the corrections for the shap and for the corners in channels having sections other than circular or flat. Keulegan studied Bazin's experiments and found both corrections to be small. Powell, on the other hand, found an appreciable corner-correction which changes the coefficient $5.75 \sqrt{g} = 32.65$ ft$^{1/2}$ per sec to 42. It is evident that this value cannot be true for every shape.

This point must be cleared and this can only be done by studying as many observations as possible. The data from thousands of observations are to be found in the literature. Someone must do the tedious work. New observations are made daily. Special series may be made in which only R and $\underline{R}$ are varied but the shape and k are kept constant (triangular channels for instance).

Will Powell act as the clearing center to whom we shall send our observations?

There is one point only on which I have a different opinion than Powell. In order still more to simplify his formula he changes k into another length, ϵ, which is a multiple (in his example the fivefold) of the sand-roughness k. I regret this as k is a dimension that can be realized. In many cases it has the order of magnitude of the height of the roughness elements. Delft students are able to make an estimation of k of a fire hose or of a gravel bed or of the inner wall of a rusted steel pipe by looking at it and feeling it. It is real; ϵ is not. In my opinion, it is worth the introduction of a coefficient to have something real. Strickler was the first who introduced it in Manning's formula instead of n, and Nikuradse found nearly the same values. It was a great improvement compared with the older tables of Bazin's γ or Manning's n, which cannot be visualized. Let us not return to them if it is not necessary.

One last remark. Why not combine the graphs of Figures 1 and 5? It is easy to indicate lines of equal R/C in Figure 1 or lines of equal Reynolds number in Figure 4.

References

COLEBROOK, C. F., Turbulent flow in pipes, with particular reference to the transition region between smooth and rough pipe laws, J. Inst. Div. Engr., February 1949.

JORISSEN, L., Pressure losses in new steel commercial pipes, Paper 3-1, Inter. Assn. Hydraulic Structures Res., Grenoble, September 1949.

James F. Halsey (Department of Theoretical and Applied Mechanics, University of Illinois, Urbana, Illinois, received December 21, 1950)--Powell has proposed a sweeping revision of the engineer's concept of flow in open channels. Since his thoughts are so far-reaching, the writer intends to cover only one point; that is, what is the effect of slope upon his Eq. (8)

$$C = 42 \log_{10} (R/\epsilon)$$

and the subsequent effect of slope upon his plot as shown by Figure 5.

Eq. (8) implies that Chezy's coefficient, C, is dependent solely upon the hydraulic radius, R, and the roughness measure, ϵ. Presumably, the constant 42 takes care of the effect of all other variables, or more correctly it may be said that the constant masks the effect, if any, of other variables. Therefore, it is correct to make the following statement concerning (8): "For any given channel, the hydraulic radius and the roughness fix the value of the Chezy C."

Such a statement may be investigated by a study of the manner in which Chezy's C is evaluated from experimental data; that is, $C = V/\sqrt{RS}$. It is necessary to measure only the hydraulic radius, the slope of the hydraulic grade line, and the mean velocity of flow in the cross-section. In the laboratory, under conditions of uniform flow, the slope, S, is equal to the bed slope and may be determined by precise levels; the hydraulic radius, R, is determined by the geometry of the channel and measurements of depth by point gage. The mean velocity, V, is usually found by evaluating the rate of flow by meters or by weight.

If the normal-depth-discharge relationship curves for a channel can be determined from a series of tests in which the bed slope is the only variable, one could expect the test results to show a family of courves, parallel to one another, and separated only by different values of the exponent of the slope. Furthermore, if the values of the slope are known, the family of curves can be reduced to a single curve, as has been done in Figure 8.

Figure 8 is a plot of the normal-depth-discharge relationship for a 90° triangular flume as evaluated from data presented in a graduate thesis written by BJELLAND [see References at end of Owen discussion]. The walls of the flume were made of plywood with several coats of varnish applied thereto. The abscissa, y_n, is the normal depth, in feet. The ordinate is the rate of flow, Q, cfs, divided by the square root of the respective bed slopes for the experimental points in question. The equation of the line in Figure 8 can be written in the more general form of

$$Q/\sqrt{S} = \phi y_n^{\,n} \quad \text{or} \quad Q = \phi \sqrt{S}\, y_n^{\,n} \qquad \ldots\ldots\ldots\ldots\ldots\ldots (23)$$

Table 3--Values of Chezy's C and R/C for a smooth 90° triangular flume with a variable slope

y_n	C	R/C			
	Eq. (26)	S = 0.00056	S = 0.001	S = 0.002	S = 0.0026
0.15	106.3	120	169	225	255
0.20	110.1	185	246	348	396
0.30	117.0	336	446	630	720
0.40	119.9	523	695	985	1120
0.50	123.2	731	970	1375	1569
0.60	126.2	960	1278	1805	2055
0.70	128.8	1210	1609	2275	2590
0.80	130.8	1480	1965	2780	3165
0.90	132.6	1768	2345	3320	3790

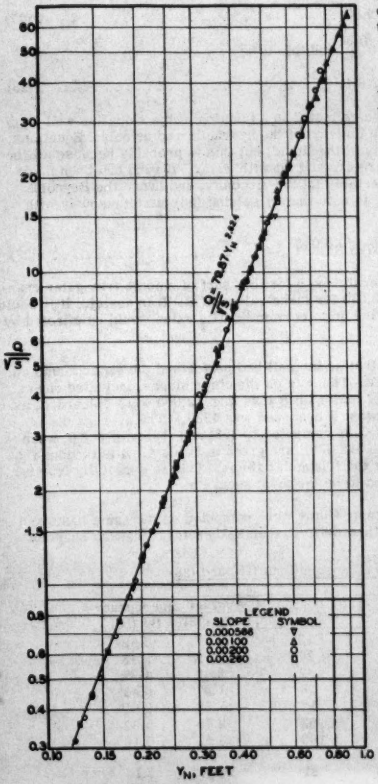


Fig. 8--Reduced rating curve for a smooth 90° triangular flume

so that ϕ and the exponent, n, can be said to be channel characteristics. From (23) it follows that

$$V = Q/A = \phi \sqrt{S}\, y_n^{\,n}/(y_n^{\,x} + k y_n) \quad \ldots (24)$$

where k and x express the geometrical configuration of the channel. For a 90° triangular channel x = 2 and k = 0; hence

$$V = \phi \sqrt{S}\, y_n^{\,n-2} \ldots\ldots\ldots (25)$$

Chezy's C may now be written as

$$C = \phi \sqrt{S}\, y_n^{\,n-2}/\sqrt{RS} = \phi\, y_n^{\,n-2}/\sqrt{R} \quad \ldots (26)$$

Eq. (26) states, in a different manner, the same thing as (8) does; that is, "Chezy's C is dependent solely upon the hydraulic radius R and the channel characteristics, ϕ and n."

However, in attempting, from Bjelland's data, to define the curve of C versus R/C, with $\epsilon/R = 0$, similar to the straight line shown by Powell in his Figure 5, the writer found a family of curves in which slope was a parameter. It seems reasonable that this should occur, since slope does not appear as a factor in the computation of ordinate, C, (either by (26) or (8)), but does appear in the abscissa. For a given channel any two conditions of flow for which y_n, ϵ, and ν are constant, but for which S varies, will produce identical values of C from (26) or (8), but different values of R/C. Thus, even though ϵ be a constant, the plot of C versus R/C can be a single curve only if the slope is constant. Table 3 contains the values of C and R/C as evaluated from the experiments cited herein.

In conclusion, it may be stated that (a) the form of (8) is substantially correct but may need modification when more experimental data become available, and (b) Figure 5 (which is a modification of the Stanton-Pannell pipe diagram) appears to be misleading for it implies that a single curve (as in pipes) expresses flow in any smooth open channel at any slope. The use of such a curve is open to question and further study.

Ralph W. Powell (Ohio State University, Columbus, Ohio, Author's closure)--The writer desires to thank Owen, Thijsse, and Halsey for their discussions. The dimensionless form of equations used by them is theoretically preferable to that used in the paper, because a quantity like $C/\sqrt{g}$ has the same numerical value in all systems of units, but probably American engineers will prefer to have the value of g in ft-sec units included with the numerical constants.

The experimental work done at the University of Illinois and reported by Owen and Halsay was on a very smooth channel, so that it does not apply to the immediate subject of this paper, except as (10) is supposed to cover this case when $\epsilon = 0$. We will eagerly await experiments made when this flume is roughened. It must be realized that (8) was meant to apply only to rough channels at high Reynolds numbers. Therefore, tests on the Illinois smooth flume cannot be used to investigate the correctness of (8). But they are appropriate to investigate (10) when $\epsilon = 0$, that is, the smooth channel formula proposed in the writer's earlier paper [POWELL, 1949, see References at end of paper].

Halsey's equation for a symmetrical 90° triangular flume

$$Q/\sqrt{S} = 79.87\, y_n^{2.624} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (27)$$

leads to $V = 79.87\, y_n^{0.624}\, S^{0.5} = 152.8\, R^{0.624}\, S^{0.5}$, and this to

$$C = 152.8\, R^{0.124} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (28)$$

Thus we can say either that Bjelland's data indicate that C is a function of the slope (as well as of the Reynolds number), or we can say that it is a function of the hydraulic radius only. Equations (27) and (28) make C independent of the viscosity of the liquid, but this is probably because all the runs were made at very nearly the same temperature and all with water. If runs had been made with liquids of various viscosities, it is quite certain that the viscosity, and hence the Reynolds number, would enter into (27). It is interesting to note that by solving (28) simultaneously with the Manning formula (11), we have

$$n = 0.009725\, R^{0.043} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (29)$$

which indicates that for water at ordinary temperatures, n for this sort of smooth triangular channel varies from 0.009 for small values of R to 0.010 for large values of R. It is doubtful if it would have been so nearly constant for other shapes, and quite certain that its value would be affected by changes in the viscosity of the liquid.

By correspondence with Owen it was found that he himself had performed the experiments on the 0.0026 slope, and he kindly furnished the data. The data on the other slopes, including one of 0.0029, was obtained from Bjelland's thesis. All runs with R less than 13,000 were discarded, as the flow appeared to be partly laminar. (The lowest R observed was 4280.) The average discrepancies from the observed C of the values of C as computed by (28) and (10) with $\epsilon = 0$, when R was greater than 13,000 (the highest value was 315,000), are given in Table 4. It is obvious that (28) gives a much better agreement than (10) for the triangular flume. This is especially true for the runs at slope 0.0026, which might be expected to be the most accurate.

The writer's results from a smooth rectangular flume were computed on the same basis and included in Table 4. Here (10) fits much better than (28). It seems, therefore, that the shape of

Table 4--Discrepancies in C by equations (10) and (28)

Experiments	Slope	No. of runs	Average discrepancy	
			By (28)	By (10)
Illinois triangular flume	0.000566	10	5.01	6.69
	0.0010	24	3.12	5.43
	0.0020	32	2.48	4.97
	0.0026	26	1.87	6.41
	0.0029	17	7.69	8.91
	Average of first	92	2.75	5.68
	Average of all	109	3.52	6.19
Author's rectangular flume	0.00035 to 0.0078	21	10.65	2.14

the cross-section is quite important, and that the same equation cannot be used for triangular and rectangular flumes without some sort of corrective term. This correction can hardly be that proposed by KEULEGAN [1938], because his slope correction for triangular channels changes C by only 3.46, while the correction for rectangular channels varied from zero to 3.5.

The question remains as to whether some equation of the form

$$C = M \log_{10} (R/C) + N \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (30)$$

might not fit the data for triangular channels as well or better than (28). This was tried for the 0.0026 slope, M and N being fitted by least squares. The result was

$$C = 19.49 \log_{10} (R/C) + 60.1 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (31)$$

This gave an average discrepancy between the computed and observed values of C of 1.64, which is less than that given by (28). It would seem, therefore, that an equation of the form of (30) may apply to all shapes of cross-section, but that the particular form (10) applies only to rectangular sections. The matter is obviously in need of further research.

The writer is very glad to have found such a powerful supporter of his general position as Thijsse. His statement that the value 42 in (10) cannot hold for all shapes is borne out by the Illinois tests. His suggestion that pertinent data be sent to the writer is very welcome. His plea that k be retained in the formula instead of ϵ is most interesting. If, as appears from the above, N in (30) cannot be always taken as zero, there is no reason why k might not be retained. It must be pointed out, however, that there is nothing inherently superior in the Nikuradse scale of roughness except priority. There is some spacing of particles of any particular shape for which ϵ would be the height of the particle. For the square battens used by the writer [1946], the necessary spacing was about ten times the height.

Combining or not combining Figures 1 and 5 is a matter of personal preference. The writer finds it difficult to read any diagram which attempts to plot four variables at once. But it is perfectly true that it can be done. The corresponding diagram for pipes was published by ROUSE [1942].

References

KEULEGAN, G. H., Laws of turbulent flow in open channels, Res. Pap. 1151, J Res., Nat. Bur. Stand., v. 21, pp. 707-741, Dec. 1938.

ROUSE, HUNTER, Evaluation of boundary roughness, Proc. Second Hydraulics Conference, Iowa City, Iowa, 1942, p. 405. (Nearly the same graph is given in his Mechanics of Fluids, 1946, p. 211; and in his Engineering Hydraulics, 1950, p. 405.)

BIBLIOGRAPHY

BIBLIOGRAPHY: GENERAL

ALASKAN SCIENCE CONFERENCE, Reports and papers presented at the Conference, November 9-11, 1950, Natl. Res. Coun. Bull. 122, 216 pp., 1951

AMERICAN GEOLOGICAL INSTITUTE, Outstanding aerial photographs in North America, Rep. no. 5, Natl. Res. Coun., 87 pp., 1951.

BULLEN, K. E , Venus and the Earth's inner core, Mon. Not. R. Astron. Soc., v. 110, no. 3, pp. 256-259, 1950 [abstr. in Phys. Abstr., v. 54, no. 640, p. 269, 1951].

DUE ROJO, A., El fundador de la heliofísica, Urania, v. 35, no. 223-224, pp. 121-137, 1950.

ENGINEERING COLLEGE RESEARCH COUNCIL, University research potential, a survey of the resources for scientific and engineering research in American colleges and universities, 114 pp., June 1951.

FESTA, C., and M SANTANGELO, A method of determining the age of the Earth, An. Geofis., v. 3, pp. 251-261, 1950 (in Italian) [abstr. in Phys. Abstr., v. 54, no. 640, p. 372, 1951].

GARLAND, G. D., Combined analysis of gravity and magnetic anomalies, Geophysics, v. 16, pp. 51-62, 1951 [abstr. in Phys. Abstr., v. 54, no. 641, p. 456, 1951].

HARDTWIG, E., Mathematical problems in geophysics, An. Geofis., v. 3, pp. 315-335, 1950 (in German) [abstr. in Phys. Abstr., v. 54, no. 640, p. 371, 1951].

MIHOLIC, STANKO, Determination of the age of igneous rocks, J. Chem. Soc., pp. 3402-3405, 1950 [abstr. in Chem. Abstr., v. 45, no. 9, 3778b, 1951].

MINTROP, L., The economic and scientific importance of geophysical methods for the investigation of the structure of mountain ranges and of usuable deposits, Schweiz. Arch. angew. Wiss. Tech., v. 16, pp. 321-335, 1950 (in German) [abstr. in Phys. Abstr., v. 54, no. 640, p. 371, 1951].

PALUZIE BORRELL, A., Nueva teoría lunar, Urania, v. 34, no. 223-224, p. 158, 1950.

SCHNEIDER, OTTO, La edad de la Tierra, An. Soc. Cient. Argentina, v. 151, pp. 57-70, 1951.

SESTOFT, I., A geophysical theory of ice ages, Proc.-Verb., Assn. Met., IUGG, 8th Gen. Assembly, Oslo, 1948, pp. 165-168, 1950.

STRATTON, F. J. M. (Ed.), Report of the Executive Committee, 1950, Intern. Council of Sci. Unions, 78 pp., 1951.

BIBLIOGRAPHY: GEODESY

BILIMOVITCH, A., On the seasonal variation of the rotation of the Earth, C.-R. Acad. Sci., Paris, v. 231, pp. 1034-1036, Nov. 13, 1950 (in French) [abstr. in Phys. Abstr., v. 54, no. 639, p. 181, 1951].

BRAGARD, L., On the fundamental relation of dynamical geodesy, Bull. Soc. R. Sci., Liège, v. 19, pp. 475-478, 1950 (in French) [abstr. in Phys. Abstr., v. 54, no. 641, p. 383, 1951].

BRAGARD, L., On the determination of the equilibrium figure of a fluid mass in uniform rotation, Bull. Soc. R. Sci., Liège, v. 19, pp. 479-484, 1950 (in French) [abstr. in Phys. Abstr., v. 54, p. 383, 1951].

BROWNE, B. C., and R. I. B. COOPER, The British submarine gravity surveys of 1938 and 1946, Trans. R. Soc., London, Ser. A, v. 242, no. 847, pp. 243-310, 1950 [abstr. in Appl. Mech. Rev., v. 4, no. 5, p. 324, 1951].

BULANZHE, IU. D., Influence of the magnetic field on invar pendulums, Trudy geod. Inst., no. 2 (129), pp. 3-32, 1948 (in Russian).

BULANZHE, IU. D., Reasons for the determination of the density of air under the bell-glass of the pendulum apparatus for changes in temperature, Trudy Seis. Inst., Akad. Nauk USSR, no. 127, pp. 157-164, 1948 (in Russian).

BULANZHE, IU. D., On the causes of secular variation of gravity, Trudy Seis. Inst., Akad. Nauk USSR, no. 127, pp. 150-156, 1948 (in Russian).

BYRD, W O., Gravity survey and geographic positions, Geogr. Rev., v. 41, no. 2, 2 pp., 1951.

BYRD, W. O., The modern mission of geodesy, Mapping and Charting Res. Lab., Ohio State Univ. Res. Foundation, 6 pp., 1951.

CAHIERRE, LOÏC, Méthodes modernes de nivellement géométrique, Pub. Tech. Inst. Geogr. Nat., Paris, 45 pp., 15 pl., 1951.

COOK, A. H., The calculation of deflexions of the vertical from gravity anomalies, Proc. R. Soc. A, v. 204, pp. 374-395, Dec. 22, 1950 [abstr. in Phys. Abstr., v. 54, no. 639, p. 181, 1951].
de GRAAFF-HUNTER, J., The geodetic uses of gravity measurements and their appropriate reduction, Proc. R. Soc. A, v. 206, pp. 1-17, 1950 [abstr. in Phys. Abstr., v. 54, no. 641, p. 383, 1951].
ELKINS, T. A., The second derivative method of gravity interpretation, Geophysics, v. 16, pp. 29-50, 1951 [abstr. in Phys. Abstr., v. 54, no. 641, p. 456, 1951].
FERRÍN MOREIRAS, A., Sobre observaciones meridianas y en el primer vertical, Urania, v. 34, no. 223-224, pp. 145-150, 1950.
GIGAS, E., The electric eye, Geofis. Pura Appl., v. 18, no. 1, pp. 113-114, 1950 [abstr. in Phys. Abstr., v. 54, p. 383, 1951].
HEISKANEN, W , The role of gravimetry in geodesy, Mapping and Charting Res. Lab., Ohio State Univ. Res. Foundation, 7 pp., 1951.
HEISKANEN, W., The world-wide gravity program of the Mapping and Charting Research Laboratory of the Ohio State University, Mapping and Charting Res. Lab., Ohio State Univ. Res. Foundation, 7 pp., 1951.
PAHAUT, R., Sur l'emploi géodésique des projections conformes, Sur la projection conforme de Gauss utilisée au Congo Belge, Inst. R. Col. Belge, Mém., v. 5, 130 pp., 1951.
PARIISKII, N. N., The development of the theory of Borass' error for contemporary method of pendulum observations, Trudy Seis. Inst., Akad. Nauk USSR, no. 127, pp. 164-170, 1948 (in Russian).
PARIISKII, N. N., Acceleration of gravity in Tbilisi, Trudy geod. Inst., no. 6 (133), 93 pp., 1949 (in Russian).
PICHA, JAN, Gravity values on some pendulum stations in Czechoslovakia measured by the Noergaard gravimeter, Pub. Inst. Geophys. Nat., Prague, v. 4, 12 pp., 1 pl., 1950 (in Czechoslovakian with abstr. in English).
TANNI, L., and E. NISKANEN, The geoidal undulations and disturbing masses, An. Acad. Sci. Fenn., Ser. A, III, Geol.-Geogr., v. 24, 20 pp., 1951.
WARNER, J., The application of radar to geodetic surveying, Aust. J. Appl. Sci., v. 1, pp. 133-146, 1950 [abstr. in Phys. Abstr., v. 54, no. 640, p. 272, 1951].

BIBLIOGRAPHY: SEISMOLOGY

BULLEN, K. E., Theoretical travel-times of S waves in the Earth's inner core, Mon. Not. R. Astron. Soc., Geophys. Suppl., no. 6, pp. 124-128, 1950 [abstr. in Phys. Abstr., v. 54, no. 641, p. 455, 1951].
de CASTRO, H., Determination of the constants k and v_0 in the seismological formula $t = 2/k \cdot \sinh^{-1} kx/2v_0$, Ciencia, Mexico, v. 10, no. 7-8, pp. 221-222, 1950 (in Spanish) [abstr. in Phys. Abstr., v. 54, no. 641, p. 455, 1951].
d'HENRY, G., On the physical nature of microseisms, An. Geofis., v. 3, pp. 87-94, 1950 (in Italian) [abstr in Phys. Abstr., v. 54, no 640, p. 371, 1951].
DOBRIN, M. B., Dispersion in seismic surface waves, Geophysics, v. 16, pp. 63-80, 1951 [abstr. in Phys. Abstr., v. 54, no. 641, p. 456, 1951].
GIORGI, M., and E. ROSINI, On the nature of the causes of microseisms, An. Geofis., v. 3, pp. 173-213, 1950 (in Italian) [abstr. in Phys. Abstr., v. 54, no. 640, p. 372, 1951].
GOGUEL, J. M., Seismic refraction with variable velocity, Geophysics, v. 16, pp. 81-101, 1951 [abstr. in Phys. Abstr., v. 54, no. 641, p. 456, 1951].
LEET, L. DON, Earth waves, Harvard Univ. Press, Cambridge, John Wiley and Sons, Inc., New York, 122 pp., 1950 [rev. in Appl. Mech. Rev., v. 4, no. 5, p. 325, 1951].
NAKAMURA, SAEMON TARO, On the seismic energy and the age of the Earth, Sci. Reports, Geophys., Tohôku Univ., v. 2, no. 3, pp. 206-208, 1950.
NEWLANDS, M., Rayleigh waves in a two-layer heterogeneous medium, Mon. Not. R. Astron. Soc., Geophys. Suppl., no. 6, pp. 109-124, 1950 [abstr. in Phys. Abstr., v. 54, no. 641, p. 455, 1951].
SHIMAZU, YASUO, and HITOSHI TAKEUCHI, Propagation of elastic waves in a medium under finite initial tensions, Geophys. Notes, Tokyo Univ., v. 3, no. 16, 7 pp., 1950.
TAKEUCHI, HITOSHI, Diffraction of elastic waves by an elastic sphere, Geophys. Notes, Tokyo Univ., v. 3, no. 19, 28 pp., 1950.

BIBLIOGRAPHY: METEOROLOGY

ARZT, THEODOR, Die Windverhältnisse in der Rhön unter besonderer Berücksichtigung der Ausnutzbarkeit des Windes als Energiequelle, Berichte, Deuts. Wetter., U.S. Zone, Bad Kissingen, no. 21, 31 pp., 1951.
BERGGREN, R., B. BOLIN, and C.-G. ROSSBY, On the mechanism of changes of upper flow pattern, Proc.-Verb., Assn. Met., IUGG, 8th Gen. Assembly, Oslo, 1948, pp. 158-163, 1950.

BERGSTEN, KARL ERIK, Some characteristics of the dispersion of the annual precipitation in Sweden during the period 1881-1940, Lund Studies in Geography, R. Univ. Lund, Ser. A, Phys. Geogr. no. 1, 18 pp., 1950.

BJERKNES, J., Practical applications of H. Jeffreys' theory of the general circulation, Proc.-Verb., Assn. Met., IUGG, 8th Gen. Assembly, Oslo, 1948, pp. 53-55, 1950.

BOHNENKAMP, H., Die Bedeutung des Mikroklimas für die Betrachtung der Wettereinflüsse auf den Menschen, Medizin-Met. Hefte, An. Met., Hamburg, no. 5, pp. 76-77, 1951.

BOOTHALINGAM, P. N., and V. SRINIVASAN, A study of the distribution of rainfall in the peninsula (of India) associated with some pre-monsoon storms, Sci. Notes, India Met. Dept., Delhi, v. 11, no. 132, pp. 9-15, 16 pl., 1950.

BRAZOL, DEMETRIO, La temperatura biológica óptima, Meteoros, Rev. Met. Geofis., Serv. Met. Nac., Buenos Aires, v. 1, no. 1, pp. 99-106, 1951 (summary in English).

BREWER, A. W., The measurement of the water vapour content of the atmosphere by dew- or frost-point measurement, Proc.-Verb., Assn. Met., IUGG, 8th Gen. Assembly, Oslo, 1948, pp. 56-58, 1950.

BUNDGAARD, R., Forecasting by statistical and synoptic extrapolation, Proc.-Verb., Assn. Met., IUGG, 8th Gen. Assembly, Oslo, 1948, pp. 59-60, 1950.

BYERS, H. R., Thunderstorm structure and circulation, Proc.-Verb., Assn. Met., IUGG, 8th Gen. Assembly, Oslo, 1948, pp. 61-64, 1950.

CURRY, M., Klimaunterschiede und wetterbedingte Reaktionstypen, Medizin-Met. Hefte, An. Met., Hamburg, no. 5, pp. 39-53, 1951.

DARTIGUES, P , Passage d'un cyclone sur la Nouvelle Calédonie, Bull. d'Information, COEC, Serv. Central Hydrogr., Paris, v. 3, no. 6, pp. 187-190, 1951.

DEIJ, L. J. L., Heat balance measurements, Proc.-Verb., Assn. Met., IUGG, 8th Gen. Assembly, Oslo, 1948, pp. 65-66, 1950.

DESAI, B N., Some aspects of tropical meteorology with special reference to the Indian weather--An examination of Malurkar's concepts regarding them, Indian J. Met. Geophys., India Met. Dept., Delhi, v. 2, no. 2, pp. 113-120, 1951.

EADY, E. T., The theory of development in dynamical meteorology, Proc.-Verb., Assn. Met., IUGG, 8th Gen. Assembly, Oslo, 1948, pp. 72-81, 1950.

FREIESLEBEN, H. C., Die Strahlenbrechung in geringer Höhe über Wasseroberflächen, Deuts. Hydrogr. Zs., Hamburg, v. 4, no. 1-2, pp. 29-44, 1951 (summaries in English and French).

GADRE, K. M., Micro-climatic survey of a sugarcane field, Indian J. Met. Geophys., India Met. Dept., Delhi, v. 2, no. 2, pp. 142-150, 1951.

GODSKE, C. L., Representativeness, a fundamental problem in meteorology, Proc.-Verb., Assn. Met., IUGG, 8th Gen. Assembly, Oslo, 1948, pp. 82-86, 1950.

GORCZYNSKI, W., Sunshine recorders in America and Europe. Their comparison and interconversion, Proc.-Verb., Assn. Met., IUGG, 8th Gen. Assembly, Oslo, 1948, pp. 87-88, 1950.

GÖTZ, F. W. P., Optics of the turbid atmosphere, Proc.-Verb., Assn. Met., IUGG, 8th Gen. Assembly, Oslo, 1948, pp. 89-95, 1950.

HESSELBERG, TH., The recent variations of the climate of Norway, Proc.-Verb., Assn. Met., IUGG, 8th Gen. Assembly, Oslo, 1948, pp. 96-103, 1950.

INDIA METEOROLOGICAL DEPARTMENT, Vagaries of the southwest monsoon, 1950, Indian J. Met. Geophys., Delhi, v. 2, no. 2, pp. 96-100, 1951.

KOTESWARAM, P., Physical properties of the upper atmosphere over India, Indian J. Met. Geophys., India Met. Dept., Delhi, v. 2, no. 2, pp. 101-112, 1951.

LANDSBERG, H., Origin and physics of the atmosphere, Trans. N. Y. Acad. Sci., Ser. II, v. 13, no. 5, pp. 154-159, 1951.

LUNELUND, H., Radiation climate of Finland, Proc.-Verb., An. Met., IUGG, 8th Gen. Assembly, Oslo, 1948, pp. 115-122, 1950.

LYSGAARD, L., Recent climatic fluctuations, Proc -Verb., Assn. Met., IUGG, 8th Gen. Assembly, Oslo, 1948, pp. 123-126, 1950.

MARCHETTI, ADOLFO A., Oscilaciones extremas de la cantidad de precipitación en la República Argentina, Meteoros, Rev. Met. Geofis., Serv. Met. Nac., Buenos Aires, v. 1, no. 1, pp. 46-54, 1951 (summary in English).

MERCANTON, P. L., Les recherches de technique pluviométrique de la Station Centrale Suisse de Météorologie, Proc.-Verb., Assn. Met., IUGG, 8th Gen. Assembly, Oslo, 1948, pp. 129-133, 1950.

MIRONOVITCH, V., Perturbations troposphériques et substratosphériques, Mét. Nationale, Paris, Mémorial, no. 32, 97 pp., 1949.

MOOLEY, D. A., Normal density distribution in the atmosphere, Indian J. Met. Geophys., India Met. Dept., Delhi, v 2, no. 2, pp. 127-137, 1951.

NEIBURGER, M., Physical processes associated with summer stratus in California, Proc.-Verb., Assn. Met., IUGG, 8th Gen. Assembly, Oslo, 1948, pp. 134-136, 1950.

OGIWARA, SEKIJI, On the solid condensation nucleus which is not soluble in water (Studies on the formation of cloud and rain, III), Sci. Reports, Geophys., Tohôku Univ., v. 2, no. 3, pp. 158-162, 1950.

OUCHI, KOO, On the stability of the ice germs in a cloud (fog) particles, Sci. Reports, Geophys., Tohoku Univ., v. 2, no. 3, pp. 163-166, 1950.
PALMEN, E., Origin of high-level cyclones south of the maximum Westerlies, Proc.-Verb., Assn. Met., IUGG, 8th Gen. Assembly, Oslo, 1948, pp. 138-147, 1950.
PRAMANIK, S. K., and P. S. HARIHARAN, Maximum dew-point temperatures in India, Indian J. Met. Geophys., India Met. Dept., Delhi, v. 2, no. 2, pp. 138-141, 1951.
QUENEY, P., Les facteurs mécaniques et thermodynamiques de la cyclogénèse, Proc.-Verb., Assn. Met., IUGG, 8th Gen. Assembly, Oslo, 1948, pp. 152-155, 1950
RAO, Y. P., and E. V. CHELAM, Vertical velocity and rainfall by convergence due to latitude effect, Indian J. Met. Geophys., India Met. Dept., Delhi, v. 2, no. 2, pp. 121-126, 1951.
SCHAEFER, V. J., The effects produced by seeding supercooled clouds with dry ice and silver iodide, Cent. Proc. R. Met. Soc., pp. 42-50, 1950 [abstr. in Phys. Abstr., v. 54, no. 642, p. 569, 1951].
SIOTANI, MASAO, Turbulence in the lowest layers of the atmosphere, Sci. Reports, Geophys., Tohoku Univ., v. 2, no. 3, pp. 167-201, 1950.
SNEYERS, R., De la correction thermique du baromètre à cuvette et à échelle fixes, Inst. R. Met. Belgique, v. 37, 16 pp., 1951.
van der HEGGE ZIJNEN, B. G., On the construction of hot-wire anemometers for the investigation of turbulence, Appl. Sci. Res., Martinus Nijhoff, The Hague, v. A2, no. 5-6, pp. 351-363, 1951.
van MIEGHEM, J., and A. VANDENPLAS, Les équations de la dynamique atmosphérique en coordonnées généralisées. Application au cas des coordonnées sphériques, Inst. R. Mét. Belgique, v. 41, 57 pp., 1950.

BIBLIOGRAPHY: TERRESTRIAL MAGNETISM AND ELECTRICITY

ABADIE, P., A. VASSY, and E. VASSY, Light of the night sky; effect of latitude, An. Geophys., v. 5, pp. 157-163, 1949 (in French) [abstr. in Phys. Abstr., v. 54, no. 642, p. 570, 1951].
ADEL, A., The emission spectra of the Earth's surface, the troposphere, and the lower stratosphere, Cent. Proc. R. Met. Soc., pp. 5-8, 1950 [abstr. in Phys. Abstr., v. 54, no. 642, p. 568, 1951].
ANONYMOUS, A new magnetic observatory, Maanmittaus (Helsinki), v. 25, p. 133, 1951 (in Finnish). [Note on projected observatory at Nurmijärvea to be built in summer of 1951.]
BALSLEY, J. R., JR., Techniques and results of aeromagnetic surveying, Intl. Assn. Terr. Mag. Elec., Bull. 13, pp. 413-418, 1950.
BEYNON, W. J. G., and G. M. BROWN, Geophysical and meteorological changes in the period January-April 1949, Nature, v. 167, pp. 1012-1014, 1951.
BLUM, E. J., and Others, On the interpretation of bursts of solar radio radiation, C.-R. Acad. Sci., Paris, v. 232, pp. 483-485, 1951 (in French) [abstr. in Phys. Abstr., v. 54, p. 467, 1951].
BLUM, E. J., and Others, A study of solar radio disturbances of feeble intensity, C.-R. Acad. Sci., Paris, v. 232, pp. 387-389, 1951 (in French) [abstr. in Phys. Abstr., v. 54, p. 380, 1951].
BOUŠKA, J., Sur l'effet terrestre apparent de l'activité solaire, C.-R. Acad. Sci., Paris, v. 232, pp. 1643-1645, 1951.
BURKARD, OTTO, Elektronenvernichtung in der F2-Schicht, Intl. Assn. Terr. Mag. Elec., Bull. 13, pp. 381-385, 1950 (summary in English).
CHAPMAN, S., Notes on aurorae and magnetic storms, I, Considerations as to a model experiment, J. Atmos. Terr. Phys., v. 1, no. 3, pp. 189-199, 1951 [abstr. in Phys. Abstr., v. 54, no. 640, p. 460, 1951].
CHAPMAN, S., Report on international collaboration to advance the study of the moon's effect upon geophysical phenomena, Intl. Assn. Terr. Mag. Elec., Bull. 13, pp. 343-345, 1950.
DUFAY, J., Bandes d'émission des molécules OH et O_2 dans le spectre du ciel nocturne, entre 9000 et 11000 A, An. Géophys., v. 7, pp. 1-8, 1951.
DUFAY, J., and M. DUFAY, Study of the emission spectrum of the night sky, from 6800 A to 9000 A, C.-R. Acad. Sci., Paris, v. 232, pp. 426-428, 1951 (in French) [abstr. in Phys. Abstr., v. 54, p. 460, 1951].
DUNGEY, J. W., Derivation of the dispersion equation for Alfvén's magneto-hydrodynamic waves from Bailey's electromagneto-ionic theory, Nature, v. 167, pp. 1029-1030, 1951.
HARRADON, H. D., Report of the Committee on Classification of Magnetic Literature, Intl. Assn. Terr. Mag. Elec., Bull. 13, pp. 321-334, 1950 [see also p. 22 of same Bull. for action taken on this report].
HASEGAWA, M., and M. OTA, On the magnetic field of S_q in the middle and lower latitudes during the II Polar Year, Intl. Assn. Terr. Mag. Elec., Bull. 13, pp. 426-430, 1950.
HERATH, FRIEDRICH, Versuchsergebnisse der luftelektrischen Höhenforschung am Aeronautischen Observatorium Lindenberg, Berichte, Deuts. Wetter., U.S. Zone, Bad Kissingen, no. 22, 30 pp., 1951 (summary in English).
INTERNATIONAL ASSOCIATION OF TERRESTRIAL MAGNETISM AND ELECTRICITY, Transactions of Oslo Meeting, August 19-28, 1948, 568 pp., Washington, 1950 (Bull. 13).

ISRAËL, H., and H. W. KASEMIR, Ueber die Schirmwirkung von Gebäuden auf die Schwankungen des atmosphärisch-elektrischen Feldes, An Géophys., v. 7, pp. 63-68, 1951.

JAHN, S., A new electrical odograph, Deuts. Hydrogr. Zs., v. 4, pp. 57-61, 1951 (in German, with English summary).

JUNG, K., Die Corioliskraft im Anfängerunterricht (An introductory mathematical treatment of the Coriolis force), Deuts. Hydrogr. Zs., v. 4, pp. 46-51, 1951 (summary in English).

KAHN, F. D., On the expulsion of corpuscular streams by solar flares, Mon. Not., R. Astr. Soc., v. 110, pp. 477-482, 1950 (reviewed in Nature, v. 167, p. 1016, 1951].

KAPLAN, J., Laboratory studies related to the physics of the upper atmosphere, Intl. Assn. Terr. Mag. Elec., Bull. 13, pp. 474-479, 1950.

LAITINEN, P. O., and G. W. HAYDON, Analysis and prediction of sky-wave field intensities in the high-frequency band, U. S. Signal Corps, Baltimore Signal Depot, 130 pp., 1950 [abstr. in U. S. Off. Tech. Serv., Bibliogr. Tech. Rep., v. 15, p. 136, PB 103045, 1951].

LITTLE, D. E , and G. M. SHRUM, Correlation of auroral observations in the northern and southern hemispheres, Trans. R. Soc. Can., v. 44, pp. 51-56, 1950 [abstr. in Phys. Abstr., v. 54, no. 641, p. 461, 1951].

McCOMB, H. E., Report of Committee on Observational Technique, Intl. Assn. Terr. Mag. Elec., Bull. 13, pp. 336-338, 1950.

McINTOSH, D. H., Geomagnetic effects of solar flares, letter in Nature, v. 167, p. 985, 1951.

MEISSER, O., Die Spannbandmagnetnadel, Geofis. Pura Appl., Milano, v. 19, no. 1-2, 15 pp., 1951 (summary in English).

MEISSER, O., and H. JUNG, Magnetische Prospektorgeräte, Geofis. Pura Appl., Milano, v. 19, no. 1-2, 19 pp., 1951 (summary in English).

MEYER, OTTO, Über eine besondere Art von erdmagnetischen Bay-Störungen, Deuts. Hydrogr. Zs., Hamburg, v. 4, no. 1-2, pp. 61-65, 2 pl., 1951 (summaries in English and French).

NAGATA, T., Local geomagnetic anomalies in volcanic regions and their interpretation, Intl. Assn. Terr. Mag. Elec., Bull. 13, pp. 452-458, 1950.

NAGATA, T., and S. AKIMOTO, Magnetic transition points of volcanic rocks, J. Geomag. and Geoelec., v 2, no. 1, pp. 29-33, 1950 [abstr. in Geophys. Abstr., p. 221, 1950].

OTA, MASAJIRO, The position and motion of the focus of the electric current vortex equivalent to the variation-field of the terrestrial magnetism at middle latitude, Intl. Assn. Terr. Mag. Elec., Bull 13, pp. 438-442, 1950.

PARKINSON, W. D., Review of the literature on the ion balance of the lower atmosphere since 1939, Intl. Assn. Terr. Mag. Elec., Bull. 13, pp. 307-313, 1950 [abstr. in Phys. Abstr., v. 54, p. 570, 1951].

PEKERIS, C. L., Effect of quadratic terms in differential equations of atmospheric oscillations, U. S. Natl. Advis. Comm. for Aeron., TN 2314, 10 pp., 1951 [abstr. in U. S. Off. Tech. Serv., Bibliogr. Tech. Rep., v. 15, p. 150, PB 103137, 1951].

PETRIE, W., Remarks on the excitation of hydrogen and helium in the upper atmosphere, Intl. Assn. Terr. Mag Elec., Bull. 13, pp. 466-470, 1950.

ROUGERIE, PAUL, L'evolution diurne lunaire de la declinaison magnétique au Val-Joyeux, Intl. Assn. Terr. Mag Elec., Bull. 13, pp. 459-463, 1950.

RUNCORN, S. K., and Others, Discussion on the origin of the Earth's magnetic field, Intl. Assn. Terr. Mag. Elec., Bull 13, pp. 419-421, 1950.

SCHLUMBERGER, M., and G. KUNETZ, Observations sur les variations rapides des courants telluriques, Intl. Assn. Terr. Mag. Elec., Bull. 13, pp. 518-528, 1950.

SILBERSTEIN, RICHARD, Oblique-incidence propagation work at the Central Radio Propagation Laboratory, Proc. Conf. Ionos. Res., Geophys. Res. Papers No. 7, Air Force Cambridge Res. Labs., pp. 154-165, December 1950.

SINGER, S. F., and Others, Measurement of the Earth's magnetic field at high altitudes at White Sands, New Mexico, letter in Phys. Rev., v. 77, pp. 398-399, 1950 [abstr. in Phys. Abstr., v. 53, p. 782, 1950; discussion by J. v. Harlem in Deuts. Hydrogr. Zs., v. 4, p. 71, 1951].

TCHENG, MAO LIN, Mesures de la quantité d'ozone contenue dans l'atmosphère par spectrophotométrie photographique du ciel bleu au zénith, An. Géophys., v. 7, pp. 45-58, 1951.

THELLIER, E., and O. THELLIER, Recherches sur l'intensité du champ magnétique terrestre ancien, Intl. Assn. Terr. Mag. Elec., Bull. 13, pp. 422-425, 1950.

THIRLAWAY, H. I. S., Measurements of gravity in Ireland, Gravimeter observations between Dublin, Sligo, Galway, and Cork, Geophys. Mem., Dublin Inst. Adv. Studies, no. 2, pt. 2, 26 pp., 10 figs., 1951.

TSUBOKAWA, I., A new type magnetometer, J. Geomag. Geoelec., v. 1, no. 1, pp. 10-11, 1950 [abstr. in Geophys. Abstr., p. 220, 1950].

UNDERHILL, BRADFORD B., Ionospheric research at the Pennsylvania State College, Proc. Conf. Ionos. Res., Geophys. Res. Papers No. 7, Air Force Cambridge Res. Labs., pp. 143-153, December 1950.

van WIJK, A. M., and B. GOTSMAN, Note on the use of the quartz horizontal-force magnetometer for the determination of magnetic declination, S. Afr. J. Sci., v. 47, pp. 316-318, 1951.

VEGARD, L., Properties of the upper atmosphere revealed through spectral analyses of aurorae and twilight, Intl. Assn. Terr. Mag. Elec., Bull. 13, pp. 479-490, 1950.
VEGARD, L., and Others, Discussion on physical aspects of the influence of solar activity on terrestrial magnetism, Intl. Assn. Terr. Mag. Elec., Bull. 13, pp. 351-368, 1950.
VELDKAMP, J., The geomagnetic field of the Netherlands reduced to 1945.0, Nederlands Met. Inst. no. 134, 30 pp., 1951. [A new survey made during the years 1942-48, using the QHM and BMZ for intensity and a modified Kew magnetometer for declination. 392 stations occupied. Results computed in terms of six elements. Anomalies computed and charted.]
VESTINE, E. H., Report of Committee on Magnetic Secular-Variation Stations, Intl. Assn. Terr. Mag. Elec., Bull. 13, pp. 298-306, 1950.

BIBLIOGRAPHY: OCEANOGRAPHY

ATKINS, W. R. G., and Others, A balance-by-depth method for the photoelectric measurement of the vertical extinction coefficient of water, J. Mar. Biol. Assn., v. 28, pp. 751-755, 1949.
BEISEL, F., Theoretical study of waves in running water, Houille Blanche, v. 5, pp. 279-285, 1940 (in French) [abstr. in Appl. Mech. Rev., v. 4, no. 5, p. 277, 1951].
BOWDEN, K. F., The effect of eddy viscosity on ocean waves, Phil. Mag., v. 41, pp. 907-917, 1950 [abstr. in Appl. Mech. Rev., v. 4, no. 5, p. 322, 1951].
BURD, A. C., and A. J. LEE, The sonic scattering layer in the sea, Nature, v. 167, pp. 624-626, 1951.
CARRUTHERS, J. N., Some unpublished records of overall waterflow past various lightvessels off the Netherlands coast from 1939 and 1940, An. Biol., v. 6, pp. 120-121, 1949.
CARRUTHERS, J. N., and Others, Water movements at the North Goodwin light vessel, Marine Observer, pp. 36-46, January 1951.
CARRUTHERS, J. N., and Others, Studies of water movements and winds at various lightvessels in 1938, 1939, and 1940, I. At the Varne Lightship and her successors, An. Biol., v. 6, pp. 115-120, 1949.
COOPER, L. H. N., Chemical properties of the sea water in the neighbourhood of the Labadie Bank, J. Mar. Biol. Assn., v. 30, pp. 21-26, 1951.
CORKAN, R. H., The levels in the North Sea associated with the storm disturbance of 8 January 1949, Phil. Trans., Ser. A, v. 242, no. 853, 32 pp., 1950.
CRAYA, A., Critical regimes of flows with density stratification, Tellus, v. 3, pp. 28-42, 1951.
DEACON, G. E. R., Oceanographical research; applications to navigation and maritime engineering, Dock Harb. Auth., v. 31, pp. 386-387, 1951.
DEACON, G. E. R., The national institute of oceanography, Polar Record, v. 6, pp. 88-90, 1951.
DOUGUET, MAX, Rapport sur les observations faites par le Commandant Charcot au cours de sa crosière dans l'Antartique durant l'été Austral 1948-1949, II. Océanographie, pp. 69-103, Service Central Hydrogr., Paris, 1950.
FAGANELLI, A., Concentration en ions hydrogene dans le Porto Canale et la lagune de Chiaggio, Atti. Ist. Veneto, Cl. Sci. mat. nat., v. 107, pp. 51-55, 1948-49.
FUGLISTER, F. C., and L. V. WORTHINGTON, Some results of a multiple-ship survey of the Gulf Stream, Tellus, v. 3, pp. 1-14, 1951.
GALL, M. H. W., Measurements to determine extinction coefficients and temperature gradients in the North Sea and English Channel, J. Mar. Biol. Assn., v. 28, pp. 757-780, 1949.
HIDAKA, KOJI, Drift currents in an enclosed ocean, II. Geophys. Notes, Tokyo Univ., v. 3, no. 38, 3 pp., 1950; III. ibid., v. 4, no. 3, 19 pp., 1951.
INOUE, EIICHI, Interrelation between turbulent fields in ocean and atmosphere, Geophys. Notes, Tokyo Univ., v. 3, no. 36, 3 pp., 1950.
JAPAN, CENTRAL METEOROLOGICAL OBSERVATORY, The results of marine meteorological and oceanographical observations, No. 2, July-Dec. 1947, 244 pp., Tokyo, 1950.
JURVA, R., Sur les conditions de glace de la Baltique le long des côtes de Finlande, Intl. Assn. Hyd., IUGG, Proc.-Verb., 8th Gen. Assembly, Oslo, 1948, v. 2, pp. 33-37, 1950.
KETCHUM, BOSTWICK H., The flushing of tidal estuaries, Sewage Ind. Wastes, v. 23, pp. 198-208; disc. by A. M. RAWN, pp. 208-209, 1951.
LAWFORD, A. L., and V. F. C. VELEY, Variations in the length of the day, Nature, v. 167, p. 684, 1951.
LEIPPER, DALE F., Nature of ocean currents in the Gulf of Mexico, Texas J. Sci., v. 3, pp. 41-44, 1951.
LESBORDES, R., Energy in swell and chop on the sea, Rev. Gén. Hyd., v. 16, pp. 3-18, 1950 (in English) [abstr. in Appl. Mech. Rev., v. 4, no. 6, p. 388, 1951].
LIVERPOOL OBSERVATORY AND TIDAL INSTITUTE, Annual report, 1950, 16 pp., Liverpool, 1951.
MORISON, J. R., and Others, The forces exerted by surface waves on piles, J. Petr. Tech., v. 2, no. 5, pp. 149-154, 1950 [abstr. in Appl. Mech. Rev., v. 4, no. 2, p. 84, 1951].

MUNK, W. H., and E. PALMEN, Note on the dynamics of the Antarctic Circumpolar Current, Tellus, v. 3, pp. 53-55, 1951.
PETTERSSON, HANS, Radium and deep-sea chronology, Nature, v. 167, p. 942, 1951.
POMMELET, A., Grouping waves, Rev. Gen. Hyd., v. 15, pp. 308-314, 1949 (in French) [abstr. in Appl. Mech. Rev., v. 4, no. 2, p. 131, 1951].
POZARYSKA, KRYSTYNA, Recent investigations of the ocean bottom, Polish Geol. Mag., v. 5, no. 1, pp. 71-101, 1950 [in Polish; summary in English].
PRICE, W. ARMSTRONG, Barrier island, not "offshore bar", Science, v. 113, pp. 487-488, 1951.
ROSSBY, C.-G., On the vertical and horizontal concentration of momentum in air and ocean currents, I. Introductory comments and basic principles, with particular reference to the vertical concentration of momentum in ocean currents, Tellus, v. 3, pp. 15-27, 1951.
ROSEAU, M., Wave motion of the sea at a beach, C.-R. Acad. Sci., v. 231, pp. 1212-1214, 1950; v. 232, pp. 211-213, 303-306, 1951 (in French).
SAID, RUSHDI, Organic origin of some calcareous sediments from the Red Sea, Science, v. 113, pp. 517-518, 1951.
SCHELL, I. I., On the distribution of icebergs in the Northern Hemisphere with special reference to south of Newfoundland, Intl. Assn. Hyd., IUGG, Proc.-Verb., 8th Gen. Assembly, Oslo, 1948, v. 2, pp. 19-21, 1950.
SCHUMACHER, ARNOLD, Über das subtropische konverzenzgebiet im Südatlantischen Ozean, Mecking-Festschrift, pp. 41-49, 2 pl., Hannover, 1949.
SHIGLEY, C. M., Engineering problems of coastal waters, Texas J. Sci., v. 3, pp. 21-29, 1951.
SHIMIZU, T., On the variation of the monthly mean sea-level, Bull. Geogr. Surv. Inst., Japan, v. 2, pp. 1-14, 1950.
STOMMEL, H., Determination of the lateral eddy diffusivity in the climatological mean Gulf Stream, Tellus, v. 3, p. 43, 1951.
TOLSTOY, IVAN, Submarine topography in the North Atlantic Ocean, Bull. Geol. Soc. Amer., v. 62, pp. 441-450, 1951.
TUCKER, M. J., Surf beats; sea waves of 1 to 5 min period, Proc. R. Soc., London, ser. A, v. 202, pp. 565-573, 1950.
STRAATEN, L. M. J. U., Periodic patterns of rippled and smooth areas on water surfaces, induced by wave action, Proc. K. Ned. Akad. Wet., v. 53, pp. 1217-1227, 1950 [abstr. in Appl. Mech. Rev., v. 4, no. 4, p. 259, 1951].
VEVERS, H. G., Photography of the sea floor, J. Mar. Biol. Assn., v. 30, pp. 101-111, 1951.
VOIT, H., Phase differences between theoretical and observed tides, Geofis. Pura Appl., v. 17, pp. 37-39, 1950 (in German) [abstr. in Phys. Abstr., v. 54, no. 638, p. 93, 1951].
WAHL, E., Wassertemperaturmessungen an Deck und im Maschinenraum, An. Met., v. 1, pp. 7-11, 1948.
YAMAGUTI, S., On the reliability of the value of monthly mean sea-level, corrected with proper factors, as a level standard, Bull. Geogr. Surv. Inst., Japan, v. 2, pp. 15-26, 1950.
YOSHIDA, KOZO, On the mechanism of the period increase of waves in storm areas, Geophys. Notes, Tokyo Univ., v. 3, no. 24, 1950.
YOSHIDA, KOZO, On the ocean wave spectrum, with special reference to the beat phenomena and the "1-3 minute waves," Geophys. Notes, Tokyo Univ., v. 3, no. 39, 8 pp., 1950.

BIBLIOGRAPHY: VOLCANOLOGY

ARMSTRONG, H. S., Geology of Echo Township, Ontario Dept. Mines, v. 59, pt. 5, pp. 1-40, 1951.
BABET, V., Exploration géologique et minière de la Haute-Sangha et de la Region de Bouar-Baboua, Gouvernment Général de l'Afrique Équatoriale Française, Bull. du Service des Mines, Paris, 109 pp., 1948.
CORNELIUS, HANS PETER, Bemerkungen zur Geologie der Riebeckitgneise in der Grawackenzone des Semmeringgebietes, Tschermaks Min. Petr., Mitt. dritte Folge, v. 2, no. 1, pp. 24-26, 1950.
DENAEYER, M. E., A propos des phases de la mise en place des roches granitiques au Kivu, Soc. Géol. Belge, v. 73, Mém. Fasc. 2, pp. 97-110, 1949-1950.
DIETRICHSON, B., Det Kaledonske knuteområde i Gudbrandsdalen, Norsk. Geol. Tidsskrift, v. 28, no. 2-4, pp. 65-143, 1950 (in Norwegian with English summary).
DOLAR, MANTUANI, Ein Beitrag zur Charakteristik der Porphyrgesteine von So. Antum bei Lepoglava (Kroatien), Tschermaks Min. Petr., Mitt. dritte Folge, v. 2, no. 1, pp. 93-104, 1950.
DUBOUX, P. V., La pétrogenèse et la metallogenèse du domaine minier de Kilo-moto, Soc. Géol. Belg., v. 73, Mém. Fasc. 2, pp. 171-243, 1949-1950.
EBERT, H., Zur Kenntnis der Keratophyre bei Hof, Neues Jb. für Mineralogie, Abh., v. 82, no. 1-2, pp. 231-246, 1951.
GANSSER, A., Geological and petrographical notes on Gorgona Island in relation to northwestern South America, Schweiz Min. Petr. Mitt., v. 30, no. 2, pp. 219-237, 1950.

GRILL, RUDOLF, and LEO WALDMAN, Zur Kenntnis des Untergrundes der Molasse in Osterreich, Jb. Geol. Bundesanstalt, Wien Festband, 1949-1951, v. 94, pp. 1-40, 1950.
HENTSCHEL, H., Die Umbildung basische Tuffe zu Schalsteinen, Neues Jb. für Mineralogie, Abh., v. 82, no. 1-2, pp. 199-230, 1951.
HERMANN, MARGIT, Pseudobrookit Haltiger Andesit von Bicsad (Lepsibukszad), Földtani Kozlöny, v. 80, no. 10-12 (Hungarian text, pp. 381-385; German text, pp. 385-389), 1950.
HEWITT, D. F., Geology of Skead Township. Larder Lake area, Ontario Dept. Mines, v. 58, pt. 6, pp. 1-43, 1949.
HOENES, D., K. R. MEHNERT, and HANS SCHNEIDERHÖHN, Führer zu petrographisch-geologischen Exkursionen in Schwarzwald und Kaiserstuhl. Verlag E. Schweizerbartsche (Erwin Nägele), Stuttgart, 45 pp., 1949.
HOLTEDAHL, HANS, Geological and petrographical investigations in the northwestern part of the Opdal Quadrangle, Southwestern Norway, Arbok, Univ. Bergen, Naturvitenskapelig Rekke, no. 2, pp. 1-60, 1949 (1950).
ILIC, MILAN, Caracteristique générale des pegmatites de la montagne Babuna et des environs de Prilep et les minereaux utils qui se trouvent dans ces pegmatites, Bull. Mus. Histoire Nat. Paye Serbe, Ser. A, Liv. 3, pp. 135-177, 19-- (in Russian, summary in French, pp. 178-181).
JACOBSEN, WERNER, and HARRAS SCHNEIDER, Die Erzgänge des nordwestlichen Oberharzes, Geol. Jb., v. 65, pp. 707-768, Hannover-Celle, 1950.
KIMPE, W. F. M., Notes additionnelles sur la pétrologie des schistes permocarboniferes, et spécialement des roches volcaniques leucocrates dynamo-metamorphiques des Alpes Apelanes en Toscane (Italy), Soc. Géol. Belgique, Bull. no. 8-10, pp. 221-230, 1950.
KOBAYASHI, HIDEO and NAOKI KOBAYASHI, Study of the Hida Metamorphic Rocks, pt. 1, J. Geol. Soc. Japan, v. 57, no. 667, pp. 121-134, 1951 (in Japanese with English summary).
KOCH, W., and E. O. TEUSCHER, Die zonale Verteilung des Lithiums in osterzgebirgischen Greisen, Neues Jb. für Mineralogie Abh., v. 82, no. 1-2, pp. 93-110, 1951.
KURATA, NOBU, Study of the underground river covered by Nishima lava flow, Mt. Fuji, J. Geol. Soc. Japan, v. 57, no. 666, pp. 79-86, 1951 (in Japanese with English summary).
KURODA, YOSHIMASU, On the so-called sheared granites and hornblende-gneiss of Hitachi District, J. Geol. Soc. Japan, v. 57, no. 667, pp. 135-142, 1951.
LHOEST, ALB., Relations magmatiques et âge relatif de quelques gisements d'or ou cassiterite de la Province Orientale, Soc. Géol. Belg., v. 73, Mém. Fasc. 2, pp. 245-256, 1949-1950.
MARTIN, G. P. M., Vulkanische aktivitat kein Klimafactor! Schriften Naturwiss. Vereins, Schleswig Holsteins, Karl-Gripp-Festschrift, v. 25, pp. 50-55, 1951.
MATTHES, S., Die kontaktmetamorphie Überprägung basischer kristalliner Schiefer von Erbendorf in der bayrischen Oberfalz, Neues Jb. für Mineralogie Abh., v. 82, no. 1-2, pp. 1-92, 1951.
MORIMOTO, R., Petrogenic meaning of the occurrence of spinel in xenoliths, Bull. Earthquake Res. Inst., Tokyo Univ., v. 28, pt. 1-2, pp. 101-108, 1950.
NIGGLI, PAUL, Probleme der alpinen Gesteinsmetamorphose, Schweiz. Min. Petr. Mitt., v. 30, no. 2, pp. 500-538, 1950.
OFTEDAHL, CHRISTOFFER, Petrology and geology of the Rondane area, Norsk Geol. Tidsskrift, v. 28, no. 2-4, pp. 199-225, 1950.
PANTO, G., and M. FÖLDVARI, New occurrence of ophilitic gabbro in the Bódva Valley (North Hungary), Földtani Intézet, Jb. Ungarischen Geol. Anstalt, v. 39, no. 3, 15 pp., 1950.
PAPP, F., and K. BALZI, La conductibilite calorique des roches hongroises, Földtani Kozlöny, v. 80, no. 10-12, Hungarian text, pp. 390-391, French text, pp. 391-394, 1950.
PEREIRA, JUDITE dos SANTOS, Note sur la géologie et la petrographie de la Guinée Portugaise, C.-R., Première Conférence Internationale des Africanistes de l'ouest, Inst. Français d'Afrique Noire, Dakar, v. 1, p. 174, 1950.
POLANSKI, A., The alkaline rocks of the East-European Plateau, Bull. Soc. Sci. Lettres Poznán, v. 10, Ser. B, Sci., Math., Nat., pp. 119-184, 1949.
SAFIANNIKOFF, A., Les systèmes de l'Urundi et de la Ruzizi, au Kivu et les intrusions granitiques, Soc. Géol. Belg., v. 73, Mém. Fasc. 2, pp. 87-96, 1949-1950.
SCHAFFER, F. X., Geologie von Österreich, 2nd ed., Franz Deuticke, Wien, 810 pp., 1951.
STILLE, HANS, Der "subsequente" magmatismus, Miscellanea Acad. Berolinensia, Akad.-Verlag, Berlin, pp. 1-25, 1950.
SUZUKI, RENSAKA, A study of silicate melts, Tech. Rep., Tôhoku Univ. Sendai, Japan, v. 15, no. 1, pp. 11-25, 1950.
TERUGGI, MARIO E., Las rocas eruptivas al microscopio, su sistemática y su nomenclatura, Inst. Nac. Invest. Cien. Nat., Pub. no. 5, Min. Educación, Buenos Aires, 401 pp., 1950.
VALLET, J. M., Étude géologique et petrographique de la partie inférieure der Val d'Hérens et du Val d'Hérémence (Valais), Schweiz. Min. Pet. Mitt., v. 30, no. 2, pp. 322-476, 1950.
VARLAMOFF, N., Granites et minéralisation au Maniema (Congo Belge), Soc. Geol. Belg., v. 73, Mém., Fasc. 2, pp. 111-171, 1949-1950.
ZEMANN, J., Zur Kenntnis der Riebeckitgneise des Ostendes der nordalpinen Grawackenzone, Tschermaks Min. Petr. Mitt., dritte Folge, v. 2, no. 1, pp. 1-23, 1950.

BIBLIOGRAPHY: HYDROLOGY

The following items are all contained in the Procès-Verbaux of the Association of Hydrology of the International Union of Geodesy and Geophysics, and relate to the Eighth General Assembly held in Oslo, Norway, August 19-28, 1948, and published in three volumes in late 1950 or early 1951.

AHLMANN, W., Preliminary glaciological plans for the Norwegian-British-Swedish Antarctic Expedition 1949-1952, v. 2, pp. 353-356.

AHLMANN, H. W., and E. G. DROESSLER, Glacier ice crystal measurements at Kebnekajse, v. 2, pp. 221-227.

ANONYMOUS, Precipitation, run-off, and losses on the Italian drainage areas--Hydrographic Service, v. 1, pp. 117-128.

BERGSTEN, F., The duration of the water-stages of the Swedish Lakes Vänern and Storsjon, v. 1, pp. 335-343.

BOGÁRDI, J., Report on the ground-water conditions of the Great Hungarian Plain, v. 3, pp. 256-265.

CASTANY, G., Étude de la surface libre des nappes par les cartes des courbes isopiézométriques, v. 3, pp. 66-76.

CHURCH, J. E., Standardizing method of snow-cover measurement, v. 2, pp. 118-127.

DEBSKI, K., La vitesse admissible et la force d'entrainement admissible dans le lit de la Vistule, v. 1, pp. 275-292.

de MARCHI, G., Caractéristiques hydrologiques et hydrauliques des Grands Lacs Subalpins, v. 1, pp. 327-331.

de QUERVAIN, M., Ueber den Abbau der Alpinen Schneedecke, v. 2, pp. 55-68.

de SAMPAIO FERRAZ, J., Northern sea ice and rainfall in S.E. Brazil, v. 2, p. 22.

DEVIK, O., Ice formation in lakes and rivers, v. 2, pp. 359-366.

DEVIK, O., Supercooling and ice formation in open waters, v. 2, pp. 380-389.

DEY, L. J. L., The lysimeter station at Castricum (Holland), v. 3, pp. 11-15.

DICKINSON, S. B., Underground water in South Australia, v. 3, pp. 272-280.

DIENERT, F., and A. GUILLERD, Mouvement de l'eau dans les lacs, v. 1, pp. 379-385.

DIENERT, F., and _. HENIN, Du bilan de l'eau, v. 1, pp. 107-115.

EKSTRÖM, G., Infiltration in relation to permeability in Swedish soils, v. 3, pp. 20-24.

FAEGRI, K., On the variations of western Norwegian glaciers during the last 200 years, v. 2, pp. 293-303.

FIELD, W. O., The variations of Alaskan glaciers (1935-1947), v. 2, pp. 277-282.

FROSINI, P., Discharge measurements of suspended load in the Reno and Tevere Rivers and other studies on the suspended load in the streams, v. 1, pp. 269-274.

FRY, A. S., Recent developments in hydrology with respect to stream-flow forecasting, v. 1, pp. 143-151.

GERDEL, R. W., Physical changes in snow-cover leading to runoff, especially to floods, v. 2, pp. 42-54.

GOLDSCHMIDT, M. J., Storm water run-off in Palestine, v. 1, pp. 228-250.

GORTANI, M., Proposal to classify genetically the thermal Italian springs, v. 3, pp. 145-153.

GUIGUE, S., and G. BETIER, Les sources thermo-minérales de l'Algérie, v. 3, pp. 117-120.

GUYTON, W. F., Fluctuations of water levels and artesian pressures in wells in the United States; their measurement and interpretation (I), v. 3, pp. 85-93.

HAEFELI, R., and P. KASSER, Observations in the Firn and Ablation Regions of the Great Aletsch Glacier, v. 2, pp. 306-322.

HARBECK, G. EARL, JR., Present status of work on evaporation in the United States, v. 1, pp. 98-104.

HARDING, S. T., Statistics of lake levels, v. 1, pp. 349-357.

HEINSHEIMER, G., On the relation of precipitation accumulation and melting of snow to the stream flow in the San Juan River, Argentina, v. 2, pp. 101-108.

HOECK, E., Sur les mesures pluviométriques dans le bassin de la Baye de Montreux, v. 1, pp. 180-190.

HOOVER, O. H., Effects of Chinook (Foehn) winds on snow cover and runoff, v. 2, pp. 86-100.

HYNIE, O., Cases of extreme abundance of ground waters in Czechoslovak Republic, v. 3, pp. 267-271.

INDIA METEOROLOGICAL DEPARTMENT, Observations of Himalayan snowfall and snow-cover, v. 2, pp. 109-114.

JOHNSSON, H., Wind currents in Lake Klammingen, v. 1, pp. 367-372.

KAITERA, P., Keeping water from freezing by means of compressed air, v. 2, pp. 390-398.

KENT, L. E., Thermal water of the Union of South Africa and South West Africa, v. 3, pp. 201-228, 3 pl.

KLAEBOE, H., Fluctuation in run-off, v. 1, pp. 213-214.
KLEIN, G. J., Canadian survey of physical characteristics of snow covers, v. 2, pp. 138-152.
KOCH, P., and A. VIBERT, Variations du niveau d'eau et de la pression ascensionnelle dans les puits: Leur mesure el leur interpretation, v. 3, pp. 57-65.
LAMBOR, J., La genese de la glace flottante et son apparition sur les cours d'eau de l'Europe centrale appartenant au bassin baltique, v. 2, pp. 367-379.
LANE, E. W., Recent progress in the United States in the study of the properties and movement of sediment, v. 1, pp. 253-262.
LEGGET, R. F., Canadian interest in snow and ice research, v. 2, pp. 128-137.
LINSLEY, R. K., L. W. FOSKETT, and M. A. KOHLER, Use of electrical analogy in flood wave analysis, v. 1, pp. 221-227.
MEEK, V., Glacier observations in the Canadian Cordillera, v. 2, pp. 264-275.
MELIN, R., Currents caused by water flowing through lakes, v. 1, pp. 373-377.
MELIN, RAGNAR, Evaporation in Sweden, v. 1, pp. 62-64.
MÖRIKOFER, W., Dependence on altitude of the snow cover in the Alps, v. 2, pp. 161-170.
MOSONYI, E., Natural storage effect in the mountainous drainage areas of the Carpathian Basin v. 1, pp. 169-176.
MUSGRAVE, G. W., Infiltration, v. 3, pp. 25-30.
NETHERLANDS STATE INSTITUTE FOR WATER SUPPLY, The effect of the yearly fluctuations in rainfall on the flow of ground water from an extended area of recharge, v. 3, pp. 47-56.
OESTERHAUS, M., Mehrjärige periodische Schwankungeń der Abflussmengen des Rheins bei Basel, v. 1, pp. 191-202.
OPPENHEIM, V. E., Deglaciation in Colombia, South America, v. 2, pp. 285-287.
OSTROMECKI, J., Les recherches de l'équilibre du bilan d'eau des bassins marécageux améliorés, v. 1, pp. 75-82.
PARDÉ, M., Influence de la couverture nivale sur le ruissellement et spécialement sur les inondations, v. 2, pp. 175-181.
PARDÉ, M., Investigation sur la chronologie des averses, v. 1, pp. 203-208.
RAFFO, J. M., Equipment to perform gaugings from the margins, v. 1, pp. 217-220.
RAMDAS, L. A., Report on evaporation from bare soil in relation to the depth of the water table or the zone of saturation, v. 3, pp. 16-19.
RENAUD, A., and P. L. MERCANTON, Les sondages sismiques de la Commission Helvétique des Glaciers, v. 2, pp. 346-352.
RENQVIST, H., Lake level statistics from Finland, v. 1, pp. 358-359.
RHODES, F. L., and W. T. WILSON, The cooperative snow investigation program: Its objectives and operations, v. 2, pp. 69-85.
ROA, D. V., Ground-water studies in Hyderabad (India), v. 3, pp. 231-247.
ROSLONSKI, R., Le bilan du circuit des eaux d'un bassin et la méthode de son calcul, v. 1, pp. 83-97.
ST. BAC, M. STANISLAW, Transpiration des végétaux de prairies et évaporation des sols non-couverts, v. 1, pp. 65-74.
SCHAEFER, V. J., The development of a snow classification system, v. 2, pp. 157-160.
SCHAEFER, V. J., The formation of ice crystals in the laboratory and in the atmosphere, v. 2, pp. 186-210.
SCHOELLER, H., La thermique des eaux souterraines d'origine profonde, v. 3, pp. 109-116.
SCHOELLER, H., Les modifications de la composition chimique de l'eau dans une même nappe, v. 3, pp. 124-129.
SCHOELLER, H., Les variations de la composition chimique de l'eau dans les nappes souterraines, v. 3, pp. 130-144.
SIREN, ALLAN, Drainage basin evaporation in Finland, v. 1, pp. 129-130.
SMOLIK, L., Water evaporation from a South Moravian soil during the very dry year 1947, v. 1, pp. 55-59.
SÜMEGHY, J., Artesian wells of the Hungarian Basin, v. 3, pp. 177-180.
SZALAI, TIBOR, Origin of the "Juvenile" substances of the thermal waters in Hungary and their quantity of heat, v. 3, pp. 181-187.
TAYLOR, G. C., JR., Ground water in northern Chile, v. 3, pp. 248-255.
TONINI, D., On the research of a characteristic time of runoff, v. 1, pp. 131-139.
TISON, L. J., Courants dans les réservoirs et les lacs, v. 1, pp. 392-394.
TISON, L. J., Étude des conditions dans lesquelles les particules solides sont transportées dans les courants à lits mobiles, v. 1, pp. 293-310.
TISON, L. J., Variations de la hauteur piézométrique dans les nappes artésiennes, v. 3, pp. 77-84.
TISON, L. J., Variations des niveaux du lac Tanganika, v. 1, pp. 360-362.
TIXERONT, J., and E. BERKALOFF, Note sur la percolation profonde des précipitations d'eau dans les massifs calcaires en Tunisie, v. 3, pp. 31-39.
VENDL, A., Hydrogeology of Budapest bitter mineral water wells, v. 3, pp. 188-196.

VOLKER, A., Bilan d'eau du Lac Ijssel, v. 1, pp. 320-326.
VOLKER, A., Mouvements des eaux dans le Lac Ijssel, v. 1, pp. 386-391.
VOLLO, L., Variations of hydraulic level and of artesian pressure in wells of the Veneto Plain; their measurement and interpretation, v. 3, pp. 94-106.
WHITE, D. E., and W. W. BRANNOCK, Sources of heat, water supply, and mineral content of Steamboat Springs, Nevada, v. 3, pp. 168-176.
WHITE, C. M., British National Committee for Geodesy and Geophysics (hydrology), v. 1, pp. 263-268.
WICHT, C. M., Potamology in the Union of South Africa, v. 1, pp. 157-163.

BIBLIOGRAPHY: TECTONOPHYSICS

BROUWER, H. A., The movement of island arcs, Q. J. Geol. Soc., London, v. 106, no. 422, pp. 231-239, 1951.
CASSEL, F. L., Snow and ice mechanics, Civ. Eng. Pub. Works Rev., v. 45, no. 533, pp. 715-717, 1950 [abstr. in Appl. Mech. Rev., v. 4, no. 6, p. 386, 1951].
FOURMARIER, PAUL, Schistosité, foliation et microplissement, Archives des Sciences, v. 4, Fasc. premier, pp. 5-24, 1951.
GUIMARÃES, DJALMA, Pattern of the geodynamic evolution of the Brazilian shield and its influence on metallogenesis, Bol. Asoc. Brasil. Metais, São Paulo, v. 6, pp. 205-223, 1950 [abstr. in Chem. Abstr., v. 45, no. 9, 3770b, 1951].
HAGIWARA, T., T. RIKITAKE, K. KASAHARA, and J. YAMADA, Observations of the deformation of the Earth's surface at Aburatsubo, Miura Peninsula, pt. 2 and 3, Bull. Earthquake Res. Inst., Tokyo Univ., v. 27, pt. 1-4, pp. 35-44, 1949 [abstr. in Appl. Mech. Rev., v. 4, no. 6, p. 389, 1951].
KATO, IWAO, Some analyses of geological phenomena by means of magnetic orientation of rocks, J. Japan Assoc. Mineral, Petrol. Econ. Geol., v. 33, pp. 27-33, 35-43, 1949 [abstr. in Chem. Abstr., v. 45, no. 9, 3773h, 1951].
KING, PHILIP B., The tectonics of middle North America, east of the Cordilleran system, Princeton Univ. Press, 220 pp., 1951.
KÜPPER, H., A. PAPP, and E. J. ZIRKL, Zur Kenntnis des Alpenabbruches am Westrand des Wiener Becken, Jb. Geol. Bundesanstalt, Wien, Festband, Jb. 1949-1951, v. 94, pp. 41-92, 1950.
OPPENHEIM, VICTOR, The structure of Ecuador, Amer. J. Sci., v. 248, pp. 527-539, 1950.
RUUD, I., The theory of direct contraction Avh. Norske Vidensk Akad. Oslo, I, Mat.-Nat. Kl., no. 2, 28 pp., 1949 [abstr. in Phys. Abstr., v. 54, no. 642, p. 565, 1951].
STEVENS, CH., La gemorphologie tectonique de la valée de la Haine, Soc. Géol. Belge, Mém. Fasc. 1, pp. 3-62, 1950-1951.

NOTES AND PERSONALIA

NOTES (including Corrigenda)

Corrigenda--In the issue of April 1951, the paper by J. R. Morison entitled The effect of wave steepness on wave velocity, pp. 201-206, in Figures 4 and 6, the numeral 2 is omitted before the second "cosh" in the second equation. The equation should read

$$C_T = C_{H=0} \left\{1 + (\pi H/L)^2 \left[2 \cosh^2 (4\pi d/L) + 2 \cosh (4\pi d/L) + 5\right]/8 \sinh^4 (2\pi d/L)\right\}^{1/2}$$

Fulbright Awards for 1952-1953--Announcement has been made of the availability of Fulbright Awards for study and other work in Europe and the Near East for the year starting in the autumn of 1952 covering the natural sciences as well as other fields. Applications must be mailed not later than October 15, 1951. Earlier, announcement was made of the availability of Awards for East Asia and the Pacific, with the closing date April 30, 1951. Interested persons should write to the Committee on International Exchange of Persons, Conference Board of Associated Research Councils, 2101 Constitution Avenue, Washington, D. C.

Research grants of the Arctic Institute of North America--The Arctic Institute of North America is offering several research grants for scientific investigations relating to arctic and subarctic regions, either in the field or one of the offices of the Institute. Applications should be in the hands of the Institute by November 1, 1951. Interested persons should write to Research Committee, Arctic Institute of North America, Broadway at 156th St., New York 32, N. Y.; or 3485 University St., Montreal, Canada.

Study of marine sedimentology in the Gulf of Mexico--A long-term project for the study of marine sedimentology has been started in the northern part of the Gulf of Mexico under the direction of Francis P. Shepard and Fred B. Phleger of Scripps Institution of Oceanography. This is sponsored by the American Petroleum Institute, with the cooperation of several organizations.

Bureau of Minerals Research to be established at Michigan College of Mining and Technology--Announcement has been made of plans to establish a Bureau of Minerals Research at Michigan College of Mining and Technology, the chief function of which will be the study of the beneficiation of low-grade copper and iron ores, and other Michigan minerals.

Doctorate in meteorology offered by Florida State University--The Board of Control of the State of Florida has authorized the Graduate School of Florida State University, Tallahassee, to confer the degree of doctor of philosophy in meteorology. This action has been made possible by expansion of the regular faculty of the Department of Meteorology to six members, five of whom hold the doctorate.

Study of the Gulf Stream--Ten scientists, under the direction of Frederick C. Fuglister and Valentine Worthington of Woods Hole Oceanographic Institution, are on a five-month survey of the Gulf Stream using the U. S. Fish and Wild Life Service vessel, Albatross III. The survey will carry them as far north as Iceland and as far east as England.

Conference of the Illinois State Water Survey Division--A conference on hydrology, water treatment, and radar-meteorology will be held at Urbana, Illinois, on October 1-3, 1951 on the occasion of the dedication of the new laboratory and office building of the State Water Survey Division. A. M. Buswell, Chief of the Division, has advised that details will be available soon. Inquiries should be sent to the Division headquarters in Urbana.

Meetings of the Society of Exploration Geophysicists--The Society of Exploration Geophysicists will hold a regional meeting in Pittsburgh, October 25, 1951. Ralph B. Ross of Gulf Research and Development Co. has been named General Chairman by Sigmund Hammer, President of the Society. The Pacific Coast Section will hold its annual fall meeting in Los Angeles, November 1-2, 1951. Flint Agee of the United Geophysical Co. in Pasadena is in charge of arrangements.

Advisory Committee of the Geophysical Institute, University of Alaska--Jno. A. Fleming, Merle A. Tuve, Henry G. Booker, and Henry A. Joesting have been named by Detlev W. Bronk, President of the National Academy of Sciences, as the Advisory Committee to the Geophysical Institute of the University of Alaska, as required by the law establishing the Institute.

New seismograph station--The Swedish Government has just established a new seismograph station in northern Sweden (lat. 68° N) under the direction of Markus Båth.

Geodetic study in Argentina--The Instituto de Geodesía y Topografía of the University of Tucumán, Argentina, is now offering courses with degree as surveyor and geodetic engineer. It also offers a doctorate in geodesy after six years of study.

PERSONALIA

Wouter Bleeker is Visiting Professor of Meteorology at Florida State University. He is on leave as Extra-ordinary Professor of Meteorology at the University of Utrecht and as Director of the Division for General Forecasting and Aeronautical Meteorology of the Dutch Meteorological Service. This spring he was elected the first President of the Commission for Synoptic Meteorology of the World Meteorological Organization.

Sydney Chapman of the University of Oxford, England, has been named Advisory Scientific Director and Visiting Professor of Geophysics of the Geophysical Institute of the University of Alaska. He will spend about a month at the Institute in the fall of 1951.

George V. Cohee has taken up duties as Head of the Department of Geology at the University of Arkansas. He will continue, part time, in the service of the U. S. Geological Survey.

Paul D. Foote, Vice President of Gulf Oil Co. in charge of Research Development in Pittsburgh, has been awarded the Outstanding Achievement Medal of the University of Minnesota.

Robert L. Geyer, formerly of the faculty of the School of Geology, Louisiana State University, is now engaged as a geophysicist with the Stanolind Oil and Gas Co. with headquarters in Tulsa, Oklahoma.

E. J. Gumbel has been appointed Consultant to the Applied Mathematics and Statistics Laboratory of Stanford University, Stanford, Calif., for work on industrial statistics.

Beno Gutenberg, in charge of the Seismological Laboratory of California Institute of Technology, has accepted a request by UNESCO to serve as adviser on geophysical and seismological research and teaching facilities in Turkey.

Richard Hazen, until recently a partner of Malcolm Pirnie, Engineers, in New York, has opened an office as a consulting engineer on municipal and industrial work in New York.

E. T. Heck, formerly Chief Geologist for the Quaker State Oil Refining Corp., has accepted a position in charge of geology and engineering for the Minard Run Oil Co. with headquarters in Bradford, Pa.

Raphael G. Kazmann, formerly associated with Ranney Method Water Supplies with headquarters in Columbus, has opened a consulting office on ground-water problems in Stuttgart, Arkansas.

Fred H. Klaer, Jr. has resigned his position with the Ground-Water Branch of the U. S. Geological Survey and is now engaged on work with the Ranney Method Water Supplies with headquarters in Columbus, Ohio.

Louis L. Ray, in charge of the Alaska Terrain and Permafrost Section of the U. S. Geological Survey, attended the Twenty-Fifth Anniversary Meetings of the Archiv für Polarforschung, held in June at Kiel, Germany.

Roger R. Revelle has been named Director of Scripps Institution of Oceanography. He has served as Acting Director since the resignation of Carl Eckart in 1950.

Guillermo Schulz of the National University of Tucumán, Argentina, has been named a Corresponding Member of the Bavarian Academy of Sciences.

Leon Sherman has accepted appointment as Assistant Professor of Meteorology at Florida State University. He had been Research Associate in the Institute of Geophysics at the University of California at Los Angeles.

Lorenz G. Straub, Director of the St. Anthony Falls Hydraulic Laboratory, University of Minnesota, was recently reelected President of the International Association for Hydraulic Research. The Association will hold its next meeting at the University of Minnesota in 1953.

Merrill Bernard was born on July 25, 1892 at Burlington, Iowa, and died at Washington, D. C. on April 13, 1951. He received his formal education at the North Carolina Military Academy (1907), the Military College of South Carolina (1908-1910), and the A. and M. College of Oklahoma (1911). He married Claudia Turner in 1914; they had one son who was lost in World War II.

Prior to World War I he was engaged in municipal, irrigation, and railroad engineering, principally in the States of Louisiana and Texas. Following his discharge from the Army as a First Lieutenant in 1918 he continued in general practice, and in 1924 opened an office as Consulting Engineer at Crowley, Louisiana, working chiefly on hydraulic and hydrologic projects in the South and in Central America. In 1932 the American Society of Civil Engineers published his paper "Formulas for rainfall intensities of long duration" which was followed in 1934 by perhaps his most distinctive single contribution in the field of hydrology, namely, "An approach to determinate stream flow" which included the development of the distribution graph as a continuation of the outstanding work of LeRoy K. Sherman with the unit graph. In 1934, the Mississippi Valley Committee of the Public Works Administration made an allotment to undertake a study of rainfall, runoff, and related features. Mr. Bernard was called to Washington to work with the newly established group staff. Following this work and completion of the report "Studies of relations of rainfall and runoff in the United States" (Water Supply Paper No. 772), he became Hydraulic Engineer with the Soil Conservation Service. He began his work with the United States Weather Bureau in 1937 which continued until his death. He was successively Chief, River and Flood Division (1937-1939); Hydrologic Director (1939-1946); and Chief, Climatological and Hydrologic Services (after 1946).

Of his work with the Weather Bureau, F. W. Reichelderfer, Chief of the Bureau, said, "His

career . . . . was marked throughout by the personal characteristics that reveal the man and explain his success. He had about him, in notable degree, an enthusiasm that inspired his associates and found obstacles intolerable, an imagination that made joy of planning, and an energy that forced achievements from his projects. His skill at organization was a skill of action; he found it very hard to accept delays and had little use for static things. . . ."

In addition to his regular duties while with the Weather Bureau, Mr. Bernard was given various special assignments which included a period as Meteorological Attaché to the Embassy at Moscow (1946) and Consultant to New York University on Industrial Meteorology. Certainly few members of the Section have contributed so much to our storehouse of knowledge or have spared themselves so little in work on executive and technical committees. He was author or coauthor of many important papers, bearing chiefly on hydrology, meteorology, and hydraulic engineering. He received the Norman Medal of the American Society of Civil Engineers in 1945 for his paper "Primary role of meteorology in flood flow estimating."

At the time of his death, he was President of the Association of Hydrology of the International Union of Geodesy and Geophysics, and Vice President of the Section of Hydrology of the American Geophysical Union. He had long taken an interest in the Union, serving as Chairman of the Committee on Precipitation for a number of years and in other capacities. He became a member of AGU in 1932.

W. G. Hoyt

Note: A more complete memoir of Mr. Bernard is available in mimeograph form and will be sent upon request to the office of AGU.--Ed.

Milton C. George, meteorologist, died at Ann Arbor, Michigan, September 28, 1950 at the age of 33. He was born in Cleveland, Ohio. He took his baccalaureate degree from Western Reserve University in 1939, and his master of science degree from Syracuse University in 1940. He taught and studied at the University of California in 1940-41, and served with the Air Force from 1942-1946 and was discharged as major. He then taught for a year at Stanford University and the succeeding year at the University of Hawaii. In the fall of 1948, he entered the University of Michigan, and took his doctorate in 1950. He had been a member of AGU since 1943.

Eugene A. Golomshtok, anthropologist and student of permafrost, died June 20, 1950 at the age of 53. He was born at Samara, Russia, and migrated to the United States as a young man. He took his baccalaureate degree in 1922, and his master of science degree in 1923 from the University of California. He received the doctorate from the University of Pennsylvania in 1935. His chief early interests were in the field of anthropology and ethnology, engaging in museum work and in field studies. Field studies included work in the Crimea and Indian sites in New Jersey. He was a lecturer in anthropology at Columbia University in 1938-39, and at Brooklyn College in 1939-40. During the war years his knowledge of languages made his services of great use on various war work largely in connection with a Russian dictionary. Since the war, he had been active in permafrost studies, continuing his interest in anthropology. He had been a member of AGU since 1947.

Robert A. Graham, Corrosion Engineer of the Central Electric and Gas Co. of Lincoln, Nebraska, died November 5, 1950 at the age of 64. He was born at Crete, Nebraska. He attended Doan College and the University of Nebraska. In 1937, he entered upon his work with the Central Electric and Gas Co. He had been a member of AGU since 1947.

Abd Essalam Mohamed Hussein of the Egyptian Service of Antiquities, died in 1950 at the age of 40. He was born in Monufia, Egypt, and took his diploma of Architecture, with honors, from the School of Architecture in Egypt. His interest in subsoil water and its effect on the foundations of Egyptian monuments developed his interest in ground-water hydrology, and brought him to the United States for study right after the war. He returned to his work in Egypt in 1947. He had been a member of AGU since 1946.

MINUTES OF EXECUTIVE COMMITTEE MEETING, AMERICAN GEOPHYSICAL UNION

Meeting of May 2, 1951

The meeting was called to order at 19h 30m in the Board Room of the National Research Council - National Academy of Sciences Building, 2101 Constitution Avenue, Washington, D. C., by President Walter H. Bucher.

Present--Thirty-six persons were present, namely: L. H. Adams, L. R. Alldredge, K. Hilding Beij, W. H. Bucher, Wilbur S. Burbank, Perry Byerly, Horace R. Byers, J. J. Capello, Felix Chayes, Ernst Cloos, Frank L. Culley, Morgan D. Dubrow, H. N. Eaton, Jno. A. Fleming, R. H. Fleming R. Clifton Gibbs, A. J. Hoskinson, M. King Hubbert, C. E. Jacob, Woodrow C. Jacobs, J. Wallace Joyce, W. D. Lambert, Walter B. Langbein, Esper S. Larsen, Jr., J. Putnam Marble, Leonard M. Murphy, Mary C. Rabbitt, A. C. Redfield, Irwin Roman, M. B. Smith, Waldo E. Smith, Harlan T. Stetson, Thomas P. Thayer, W. T. Thom, Jr., James T. Wilson, and George P. Woollard. The following were excused: Fred Anderegg, Robert Balk, Ralph E. Cleland, Earl Ingerson, C. O'D. Iselin, George F. McEwen, F. W. Reichelderfer, L. G. Straub, V. Vacquier, F. J. Veihmeyer, and Hurd C. Willett.

Approval of Minutes--The minutes of the meeting of November 15, 1950 were approved as published in the February 1951 issue of the Transactions, pages 141-148.

General Secretary's Report

General Activities

Executive Committee--The Committee has suffered because of the death of Merrill Bernard, President of the International Association of Hydrology, and Vice President of the Section of Hydrology. He had long been active in the Union, especially in the Section of Hydrology and its research committees. Harald U. Sverdrup is also lost to the Committee because he resumed his Norwegian citizenship on April 2, 1951.

Financial Report--As of April 1, 1951, the total liquid assets of the Union were $23,652.06, including $19,267.50 in the General Fund and $3384.56 in the Permanent Fund. On April 1, 1950, the total liquid assets were $20,171.54.

Membership--Since November 10, 1950, 288 new members have been added, making a net increase of 95 as follows:

Membership, November 10, 1950	4645	
New members, November 10, 1950 to April 30, 1951 (including 61 in process of election)	288	
Reactivated	1	4934
Resignations	159	
Deceased	13	
Inactive	16	
Dropped	6	194
Membership, April 30, 1951		4740

Thirteen deaths have been reported since our last meeting, namely: F. W. Greve, January 13, 1950; Charles C. Slayton, March 5, 1950; Ranbir Singh Shrikant, July 19, 1950; William F. Petersen, August 20, 1950; Thomas A. Blair, September 29, 1950; William G. Smiley, November 8, 1950; Leland B. Snoddy, November 12, 1950; Stanley M. McDonald, December 11, 1950; George W. Carr, December 24, 1950; Owen B. French, February 1, 1951; Harry R. Seiwell, March 5, 1951; Theodore T. Knappen, March 21, 1951; and Merrill Bernard, April 13, 1951.

Corporation Membership--Since our last meeting we have lost two corporation members, and have added two others, namely: Institute of Geophysics of the University of California, and Gulf Research and Development Company of the Gulf Oil Corporation.

Meetings--The Twenty-Sixth Regional Meeting was held in Fresno, California, February 9-10, 1950, with the Sections of Meteorology and Hydrology cooperating. About 200 were present and about 25 papers were presented. A Regional Committee has now been appointed for the South Pacific Region, including the Sections of Meteorology and Hydrology. Other Sections are invited to join. Appointments to the Committee to represent new Sections will be made on recommendation of Section officers. (This Committee, since appointed, consists of J. W. Johnson, Chairman; E. M. Vernon, Secretary; Harry F. Blaney; Harold Conkling; Morris Neiburger; and R. H. Simpson.) At the Thirty-Second Annual Meeting interest and enthusiasm seemed especially high. Programs were noteworthy in many respects and attendance at the smoker far exceeded any previous record. Over 750 registered attendance at the meetings.

Plans for formalizing the Pacific Northwest Region are nearing completion, and there has been some discussion regarding a Southeastern States Region. There has also been discussion regarding regional cooperation with the Society of Exploration Geophysicists and others in the Southern Great Plains area; Walter E. A. Ruska of the Committee on Meetings has been the clearing house for matters in this area.

A meeting in connection with the Centennial in Engineering to be celebrated in Chicago in September 1952 is under consideration and will come up for discussion later.

Publications--Currently each edition of the Transactions runs to 5200 copies. Four thousand seven hundred and forty-two copies of the April issue were mailed, not including about 200 copies to be mailed abroad later on exchange. Our present international circulation is in excess of 800 copies.

Papers of the Colloquium on Plastic Flow and Deformation within the Earth held in Hershey, Pennsylvania, last September have been received. It is planned that these shall be published as a group in the Transactions of August 1951.

Form letters regarding student subscriptions were mailed to about 200 institutions. About 20 such subscriptions have been received. A rate of $4 was established for 1951.

Office and Personnel--Arrangements have been made for quarters in the Administration Building of the Carnegie Institution of Washington through next January.

Mrs. Geraldine Lamb and Mrs. Ida A. Edwards left the staff in January. James J. Capello joined the staff in January as Assistant to the Executive Secretary and Assistant Editor. As of January 1, the office staff went under the Federal Social Security plan.

Affiliation with AAAS--With the concurrence of the National Research Council, the AGU has affiliated with the AAAS and necessary formalities will be completed shortly. The AGU will have two representatives on the Council of the AAAS.

News Items--The Institute of Geodesy, Photogrammetry, and Cartography has been established at the Ohio State University under the direction of George H. Harding, who is also Director of the Mapping and Charting Research Laboratory of the University. Walter D. Lambert, Weikko Heiskanen, and Earl Church have been appointed to the staff. A full graduate and undergraduate curriculum bearing on the broad aspects of geodesy and cartography is installed.

The Fifth General Assembly of the Pan American Institute of Geography and History was held in Santiago, Chile, October 16-27, 1950. Elliott B. Roberts represented the American Geophysical Union.

Last December 12 the Chinese communists, without warning, occupied by force the two private observatories of ZiKaWei and ZoCe near Shanghai, both belonging to the Catholic French Mission.

An invitation from the Department of State to send delegates to the Fourth International Congress of the Sea to be held in Ostend, Belgium, July 20-22, 1951, was declined as this Congress concerns itself with maritime activities outside the scope of the AGU.

The Engineering College Research Council has announced a survey of the research potential in physical sciences, engineering, and psychology in U. S. educational institutions in connection with national defense.

An invitation was received from the Massachusetts Institute of Technology to take part in a

Symposium on Hydrodynamics in Modern Technology and the dedication of the Hydrodynamics Laboratory and the Ship Model Towing Tank at Cambridge, Massachusetts, June 4-6, 1951. Herbert N. Eaton represented the AGU.

The National Academy of Sciences has established a Section of Geophysics.

Activities as Committee on Geophysics of the National Research Council

Bibliography of Hydrology--The International Association of Hydrology, in furtherance of its plans to resume publication of an international bibliography, requested the Section of Hydrology to prepare a bibliography on hydrology for the United States for the years 1941-1950. A committee of the Section of Hydrology has secured financial support for this ambitious undertaking and the National Research Council is entering into a contract with the Bureau of Reclamation and on behalf of the AGU to accomplish this purpose. Much of the bibliography has already been compiled. It is expected that future bibliographies will be compiled for each calendar year.

National Scientific Register--The AGU has been called upon to assist in this work with respect to the geophysical sciences, and took an active part in formulating the questionnaire. Envelopes for mailing questionnaires were supplied from our AGU plates.

General Assembly of the IUGG--About 60 persons have indicated their intent to attend the Ninth General Assembly at Brussels, August 21 to September 1, 1951. It is anticipated that the Department of State will appoint a number of delegates on recommendation of the National Research Council and the AGU. Others attending will be accrediated by the National Research Council.

Israel--The Government of Israel has announced the formation of a National Committee on Geophysics and it is expected that Israel will soon be added to the list of countries who are members of the IUGG.

Third Polar Year--The Mixed Commission on the Ionosphere is proposing a Third Polar Year for 1957-1958. The second was held in 1932-1933 and the first about 50 years previously. Cooperation of the AGU will follow plans to be developed at Brussels.

Joint Commission on Oceanography--Richard H. Fleming has been designated Liaison Officer from the AGU to the Commission.

K. Hilding Beij,
General Secretary

Action on the General Secretary's Report--The report was accepted.

International Matters

J. A. Fleming advised that the General Assembly of the International Astronomical Union scheduled to be held in Leningrad in the summer of 1951 has been cancelled. He also reported that the International Council of Scientific Unions (which, among others, includes the International Union of Geodesy and Geophysics) plans to hold a meeting in Washington, D. C., in October 1951 with one session open to the public. He also advised that the Division of International Relations of the National Research Council has stepped up its activity, and is serving as adviser to the Department of State on international scientific matters. W. W. Atwood, Jr. has been named Executive Secretary of the Division. He advised that the so-called Berkner report, Science and Foreign Relations, has been adopted by the Department of State, and that the recommended Science Office has been established. J. B. Koepfli of California Institute of Technology has been designated Science Adviser. (J. Wallace Joyce, President of the Section of Terrestrial Magnetism and Electricity, has since been named Consultant to the Department of State, assigned to the Science Office.)

Reports of Standing Committees

Membership--Chairman Dubrow reported increasing activity in his Committee, and felt that a membership of 5000 might well be reached within the next year.

Corporation Membership--Report was made of an application for Corporation Membership received from an agency of a foreign government. It was felt that the National Research Council is particularly concerned, but that if acceptable to the Council, the agency should be elected.

Meetings--Chairman Marble presented a summary report as shown in Appendix 1. The report was accepted.

Budget--Chairman Eaton presented the budget for the next fiscal year as shown in Appendix 2. After thorough discussion, this budget was adopted.

Reports of Special Committees

Geophysical and Geological Study of Continents--Chairman Woollard presented a brief summary of the report shown in Appendix 3.

Cosmic-Terrestrial Relationships--Chairman Stetson presented a brief summary of the report shown in Appendix 4.

Award of the William Bowie Medal--Chairman Lambert confirmed the award that was made to Harald U. Sverdrup and advised that plans are well along for the designation of the next recipient.

Resolutions--Chairman Rabbitt presented a revision of the resolution on the Third Polar Year that was referred to the Executive Committee by the Business Meeting on the afternoon of May 2, 1951. After extensive discussion, it was voted to table this matter pending action by the IUGG at the Brussels Assembly in August 1951. In the discussion it was pointed out by J. A. Fleming that the planning and execution of a Polar Year must not be entered into lightly. It is an arduous job to which proponents must devote many seemingly fruitless hours, and involves considerable financial outlay. It was mentioned that the meteorologists, strong supporters of the Second Polar Year, are not enthusiastic about a Third Polar Year because they are now securing world-wide meteorological data on a regular basis. It was also mentioned that a Third Polar Year could only be partially successful without full world-wide cooperation, especially in polar regions.

Reports of Sections

Meteorology--Secretary Jacobs mentioned the resolution passed by the Section of Meteorology relating to programs of annual meetings [see Transactions of June 1951, p. 491]. He expressed that it was his interpretation that the usual symposium is not to be supplanted, but that rather a joint meeting be arranged for especially significant papers of broad interest.

Volcanology--Report was made of the action taken by the Section of Volcanology relative to the suggestion to rename the Section [see Transactions of June 1951, pp. 492-493]. After extensive discussion, it was voted that the report be accepted and action postponed until the next meeting of the Executive Committee.

Reports of Divisions of the National Research Council

Physical Sciences--Chairman Gibbs outlined the activity of the Advisory Committee on Geophysics to the Office of Naval Research, functioning under the joint sponsorship of that Division and the Division of Geology and Geography. He noted that at the Committee's last meeting (November 20, 1950) recommendations were made with respect to 34 research proposals. Nominations for three members to replace those who are to retire on June 30, 1951 were requested for AGU.

He advised also that the volume of the Physics of the Earth Series relating to International Constitution of the Earth is undergoing revision and page proof is complete. The cost will not be more than $6.

He mentioned also the enlargement of the Division of International Relations and its close cooperation with the Department of State on science matters outside of government departments. American scientists traveling abroad would do well to get into touch with the Science Office of the State Department in order that they may have the aid of consular officers.

He presented information concerning the new fellowship program for scientists of broad training for such work as physics of the solid state and aerodynamics. Predoctoral fellowships carry a stipend of $2000 to $3200 depending upon dependency status, and the postdoctoral stipend of $4500.

Affiliation with Other Organizations

American Geological Institute--Representative Woollard reported that progress is substantial and the program is moving forward wisely.

Unfinished and New Business

A communication from the American Institute of Mining and Metallurgical Engineers concerning a joint committee on geophysics was read, requesting a collective point of view with respect to a resolution submitted to them. After brief discussion, it was voted that this resolution should not be supported.

The General Secretary reported that 179 have not paid dues from 1949 to the present. He recommended that they be dropped in accordance with statutory requirements, but with the further provision that first one more attempt be made to return them to active membership. This was approved.

Adjournment--The meeting adjourned at 22h 10m.

K. Hilding Beij, General Secretary
Waldo E. Smith, Executive Secretary

APPENDIX 1--REPORT OF THE COMMITTEE ON MEETINGS

John Putnam Marble, Chairman

Woodrow C. Jacobs
Herbert S. Riesbol
Walter E. A. Ruska
Glenn E. Stout
Frank J. Veihmeyer

This past year the Committee was reorganized so as to secure as far as possible a membership evenly distributed over the country in order to have a member "on the spot" should there be a call for a regional meeting in any section. During the year the Twenty-Sixth Regional Meeting was held at Fresno State College, Fresno, California, on February 9 and 10, 1951. About 200 attended the sessions held by the Sections of Meteorology and Hydrology.

The Thirty-Second Annual Meeting was held in Washington, D. C., on April 30, May 1 and 2, 1951, using the same meeting places as in recent years. The registered attendance was 755, slightly less than in 1950, but the total in attendance approached 1000. The evening session on April 30 and the smoker on May 1 both played to capacity houses, and the continuation of the General Session on May 2 was unusually well attended.

The Thirty-Third Annual Meeting will be held in Washington, D. C., on Monday, Tuesday, and Wednesday, May 5, 6, and 7, 1952. These are the days in the spring scientific sequence corresponding to the dates of the 1951 meeting.

The possibility of a Regional Meeting in Chicago in early September 1952 in connection with the One Hundredth Anniversary celebration of the American Society of Civil Engineers is being explored. Not all those approached have yet replied. The possibility of a Regional Meeting in the Southwest has been broached in a tentative fashion.

APPENDIX 2--REPORT OF THE COMMITTEE ON BUDGET FOR THE FISCAL YEAR ENDING JUNE 30, 1952

Herbert N. Eaton, Chairman

Jno. A. Fleming
Nathan C. Grover
H. W. Hemple
Waldo L. Schmitt

The Committee on Budget of the American Geophysical Union has conferred with the General and Executive Secretaries of the Union regarding the budget for the fiscal year July 1, 1951, to June 30, 1952, and proposes the following budget. You will note that a small excess of receipts over expenditures is anticipated, and this excess will probably be larger than that indicated, since the Committee has attempted to overestimate expenditures and to underestimate receipts slightly in order to provide some factor of safety. The Committee has reason to feel that, as it stated in its report last year, the increase in dues to $7 has placed the Union on a self-sustaining basis.

Statement of Assets and Liabilities as of June 30, 1951 (estimated)

Assets:			
General Funds:			
Cash reserve	$11,830		
Reserve for Directory	0		
Reserve for International Travel	500	$12,330	
Permanent Fund:			
U. S. Govt. bonds (at cost)	$ 2,368		
Northwest Federal Savings and Loan Account (deposits only)	992	3,360	
Robert E. Horton Fund		1,180	
William Bowie Medal Fund		60	$16,930
Bills receivable			2,800
Total assets			$19,730
Liabilities:			
Bills payable		$ 300	
Surplus		19,430	19,730

Operating Statement (General Funds)

Estimated receipts:			
National Research Council, grant		$ 400	
Miscellaneous contributions		0	
From Reserve for International Travel		500	
Income:			
Dues, 4,350 members	$30,450		
Sales, Transactions	5,600		
Sales, reprints	2,000		
Interest on investments	10	38,060	
Total receipts			38,960
Estimated expenditures:			
Publication of Transactions:			
Printing	$ 8,500		
Preparation	7,700		
Mailing	1,000		
Co-editors	1,500	$18,700	
Reprints		2,000	
General office expenses:			
Salaries	$12,600		
Stationery and supplies	1,000		
Postage and communications	1,200		
Equipment	200	15,000	
Expenses, meetings:			
Annual	$ 650		
Regional	200	850	
Expenses, Sections		100	
Expenses, Committees		600	
Travel of officers		50	
Expend from Reserve for International Travel		500	
Expend from Income for International Travel		250	
Reprints, International Association of Volcanology		300	
Miscellaneous expenses		80	
Total expenditures			38,430
Estimated excess of receipts over expenditures			$ 530

Transfers of Funds

Transfer from Cash Reserve to Reserve for Directory	750
Transfer from Cash Reserve to Permanent Fund (interest)	10

Operating Statement (Robert E. Horton Fund)

Estimated receipts	$ 0	
Estimated expenditures	200	
Estimated excess of expenditures over receipts		$ 200

Operating Statement (William Bowie Medal Fund)

Estimated receipts	$ 0	
Estimated expenditures	15	
Estimated excess of expenditures over receipts		$ 15

Statement of Assets as of June 30, 1952 (estimated)

General Funds:		
Cash reserve	$11,600	
Reserve for International Travel	0	
Reserve for Directory	750	$12,350
Robert E. Horton Fund		980
William Bowie Medal Fund		45
Permanent Fund, investments		3,370
Bills receivable less bills payable		2,500
Total assets		$19,245

APPENDIX 3--REPORT OF THE SPECIAL COMMITTEE ON THE GEOPHYSICAL AND GEOLOGICAL STUDY OF CONTINENTS, 1950-1951

George P. Woollard, Chairman

C. S. Beals
Francis Birch
Walter H. Bucher
Maurice Ewing
R. A. Geyer
Ross Gunn
H. W. Hemple
Patrick M. Hurley
Henry R. Joesting
B. Perkins, Jr.
E. B. Roberts
Howard Tatel
W. T. Thom, Jr.
James T. Wilson
J. Tuzo Wilson
J. Lamar Worzel

Regional gravity program

Global network--During 1950 the global network of gravity-meter stations being established under the auspices of the Office of Naval Research and the direction of G. P. Woollard was extended considerably. N. C. Harding of the University of Wisconsin used a high-range Worden gravity meter in developing a network of gravity stations in Africa with ties to Bermuda, Portugal, Madagascar, Malta, and Rome. C. M. Muckenfuss, also of the University of Wisconsin, used a high-range Worden gravity meter in developing a similar network of gravity stations in Australia, New Caledonia, and New Zealand with ties to Oahu, Canton Island, Fiji, Samoa, New Guinea, Tasmania, Singapore, Bangkok, Dehra Dun, New Delhi, Kashmir, Karachi, Dhahran, Manila, Tokyo, the Aleutian Islands, and Fairbanks, Alaska. Both programs owe much of their success to the excellent cooperation extended by local government and university personnel in the various countries visited. The area covered to date on the global network of gravity-meter stations is shown in Figure 1. In the summer of 1951 it is planned to repeat the world girdling traverse established in 1948 as a series of closed loops using the "leap frog" method of closure to further strengthen this base line of measurements.

Other global gravity measurements of particular interest from the standpoint of establishing the existence of fundamental differences between the continents and the ocean basins are the measurements at sea being made by personnel of the Lamont Geological Observatory of Columbia University under the auspices of the Office of Naval Research and the direction of Maurice Ewing. Current progress on this program will be presented as a separate report. Port stations of this network, as well as those of the network of submarine gravity stations established by B. L. Cooper of Cambridge University and F. A. Vening Meinesz, are also being occupied as part of the global gravity-meter network.

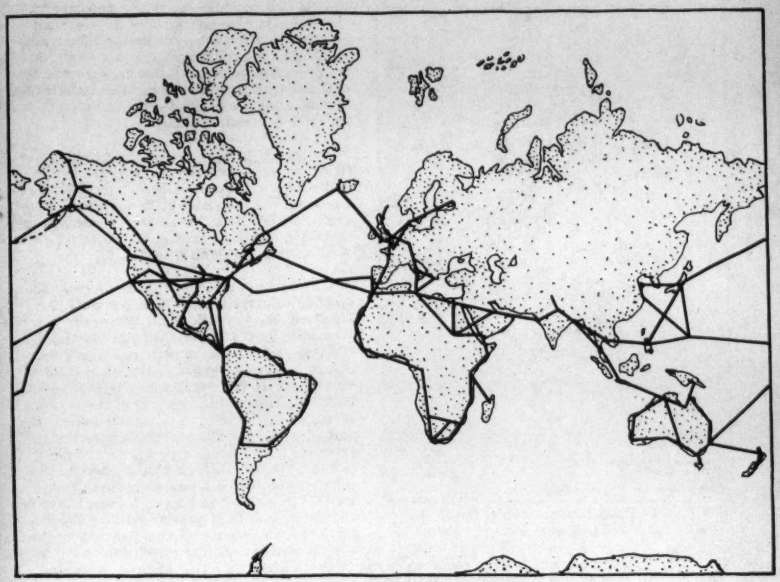


Fig. 1--World gravimetric network, 1950

Work in North America

Pendulum measurements--In North America, C. R. Shelton of the U. S. Coast and Geodetic Survey established a line of pendulum stations for use in calibrating gravimeters from Sam Fordyce, Texas, to The Pas, Manitoba, Canada. In all, 40 sets of pendulum observations were made and these, plus 39 other pendulum bases, were tied into a gravimeter network using a high-range Worden gravity meter. This network of pendulum and gravity-meter stations (see Fig. 2) covers 2300 mgal change in gravity. A comparison of the gravity differences obtained by pendulum and gravity meter based upon a least-squares adjustment of the values indicates a probable error of about $\pm$ 0.7 mgal in the pendulum values. New pendulum work planned by the U. S. Coast and Geodetic Survey includes the establishment of a series of gravity bases in Alaska.

Under the auspices of the Air Materiel Command, Cambridge Field Station, and the direction of G. P. Woollard, another line of pendulum bases had been planned for 1950 between Mexico and Alaska using quartz pendulums of the Gulf Research and Development Company. Because of instrumental difficulties, this program had to be deferred. However, a test run at the end of the summer of 1950 consisting of a loop between Washington, D. C., to Grand Forks, N. Dak., Houston, Tex., and return showed that the apparatus was in working shape, and it is planned to complete the program in the summer of 1951. As part of this program, Wm. E. Bonini of the University of Wisconsin made a run from Madison, Wis., to Fairbanks, Alaska, using a high-range North American gravity meter. Observations were made at the proposed pendulum bases at about 100-mi intervals and at auxiliary stations at about ten-mile intervals. Key points along this traverse between Madison, Wis., and Fort Nelson, Canada, were also checked using two high-range Worden gravity meters. A subsidiary line of observations also was run along the railroad from Anchorage to Fairbanks through the cooperation of the Alaska Railroad which furnished a track sedan for the purpose. In addition, gravity-meter ties were also made from Madison, Wis., to Washington, D. C., and Boston, Mass.

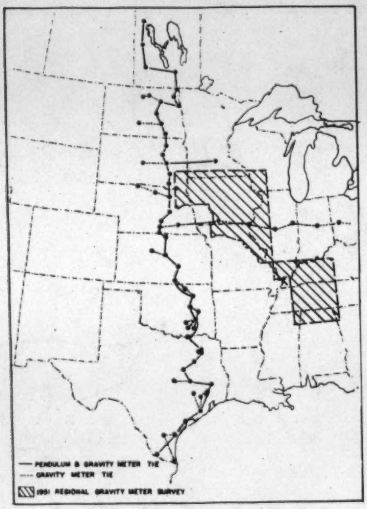


Fig. 2--Pendulum network of the U. S. Coast and Geodetic Survey, 1950

No new pendulum work was reported in Canada or Mexico and with the development of high-range gravimeters having higher precision than the pendulums it is not likely that the present pendulum-station network will be extended to any great extent. The distribution of stations in the present network in North America is shown in Figure 3.

Regional gravity-meter investigations--Gravity-meter work now in progress by the U. S. Coast and Geodetic Survey includes a regional survey (six-mile station spacing) of an area of 46,000 sq mi in western Tennessee and Kentucky, and of an area of 82,000 sq mi centered about the State of Iowa (see Fig. 2).

Under the auspices of the Geological Society of America and the direction of G. P. Woollard, W. A. Black of the University of Wisconsin used a Humble Oil and Refining Co. "Y" type exploration gravity meter in establishing a series of gravity stations at eight-mile intervals from Madison, Wis., to the Pacific Coast and back as part of the regional network being developed in the northwestern part of the United States. This network of gravity stations is being tied to that of the Dominion Observatory in Canada, and its development to date and new traverses planned for 1951 are shown in Figure 4. Black also developed a network of gravity stations covering parts of Iowa, Minnesota, and Wisconsin to outline the position of what appears to be the largest positive Bouguer anomaly area reported so far in North America. This feature, extending from central Kansas to Lake Superior, has a width averaging 35 mi and an amplitude of over 100 mgal. In Wisconsin in the area of the exposed crystalline complex it appears to be related to a basin filled with Pre-Cambrian basic lavas.

In Canada, the Dominion Observatory established 2500 new gravity-meter stations which were distributed throughout all the provinces and considerable areas of the Northwest Territories. Special attention was given to the Maritime Provinces and Alberta, though extensive traverses were made over highways connecting eastern and western Canada.

An important project completed was the regional study of an area of 130,000 sq mi west of Hudson Bay which is believed to have been the center of a former ice cap. This survey was accomplished using air transport over an area that otherwise was practically inaccessible. It is expected that an analysis of these results will indicate whether isostatic equilibrium has been reestablished after the melting of the ice or whether the land in the area is still rising. In addition, 157 gravity stations were established over an area of 485 sq mi on the ice cap on Baffin Island with the object of testing the value of the gravity method for determining ice thickness.

In Mexico, R. M. Lopez working in cooperation with the Inter-American Geodetic Survey is starting an expanded program of regional gravity measurements. Although these are being made primarily for studies of deflection of the vertical, they will contribute materially to geologic and geophysical investigations there. A similar program is also being conducted in Venezuela by A. C. Romero in cooperation with the U. S. Coast and Geodetic Survey and the Inter-American Geodetic Survey.

The development of regional gravity networks in North America are shown in Figure 5. This program is being implemented to a large extent now by contributions of data from various oil companies. Areas for which oil-company data have been released to date on a six- to eight-mile spacing in the United States to this Committee for scientific purposes or by publication are shown in Figure 6. There still remain several other areas which have been surveyed in connection with oil exploration. Negotiations are in progress to arrange for the release of regional data in these areas.

Fig. 3--Pendulum station network in North America, 1950

Local gravity-meter surveys--Of equal importance taken in gross are the numerous local gravity surveys being undertaken by the various universities. The Committee Chairman will appreciate notification of any and all such surveys so that an effort can be made to tie them into a master network having a common datum. The following programs have come to the attention of the Committee.

At Harvard University, R. J. Bean completed in 1950 a regional survey of 1100 gravity stations

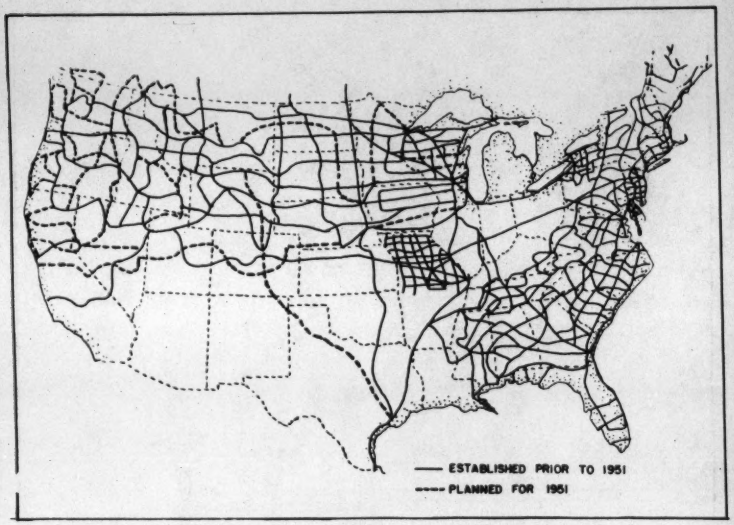


Fig. 4--Regional reconnaissance gravity traverses in the United States

covering a strip across central Vermont and New Hampshire. Analysis of this survey is now complete, and publication is planned. Of particular interest are the gravitational "lows" found to be associated with granite intrusives in this area. This relationship has also been reported in other parts of New England and the Maritime Provinces, as well as from other parts of the world. P. E. Byerly, also of Harvard University, is planning to make a strip survey across the Great Valley and Coast Ranges between the San Francisco and Coalinga regions in the summer of 1951.

At the University of Michigan, James T. Wilson reports that a regional network of 75 gravity stations was established last year in the Lower Peninsula area and that this network will be expanded this year. At the University of Minnesota, L. Bacon is making a regional survey of the Pre-Cambrian area south of Lake Superior as part of a study of the iron formations. At the University of Washington, G. E. Goodspeed reports that gravitational studies within that State are being started in 1951. At the Colorado School of Mines, Ralph Holmer has completed a regional gravity survey of the State of Colorado. At the University of Toronto, J. B. Prendergast carried out extensive gravity measurements in southern Ontario and established a line of measurements in Michigan. At Indiana University, Judson Mead advises a regional survey of Indiana is being started in 1951 using a gravity-station interval of six miles. At the University of Wisconsin, J. Belshe is making a gravimetric and magnetic survey of the crystalline complex in the Wausau, Wis., area. N. C. Harding has been making gravity and magnetic measurements in connection with seismic surveys of buried Pre-Cambrian topography in the Waterloo, Wis., area. W. A. Black has been extending the regional network of gravity stations taken at about ten-mile intervals on the principal roads covering the State. At St. Louis University, K. C. Chandiok has been making a detailed gravity survey of the St. Charles area in Missouri.

Foreign gravity work

Foreign regional gravity surveys that have been completed are in Ireland, France, Sweden, and Denmark, and surveys that are near completion or in progress are in Norway, New Caledonia, Finland, Germany, England, Italy, Argentina, New Zealand, Spain, South Africa, Japan, French Africa, Madagascar, Australia, the Philippines, and India.

Fig. 5--Regional gravity traverses in North America, 1950

High-range gravity meters suitable for regional studies are now being used by government agencies and university groups in Canada, Argentina, India, England, Venezuela, Mexico, France, Denmark, Finland, Iceland, Scotland, Italy, Australia, Yugoslavia, and the Anglo-Egyptian Sudan, as well as in the United States.

It is hoped through the global network of gravity-meter stations to get the results of all these various investigations on a common datum which should add materially to their value both for geodetic purposes and studies of Earth structure.

Absolute gravity values

Work on the direct determination of absolute acceleration of gravity by M. Volet at Paris is continuing. Alan Cook of Cambridge University is planning to connect the absolute gravity base at Teddington with that at Paris and indirectly with that at Potsdam by using the gravity base established at Gatow Airport, Berlin, by E. F. Gigas of Bamberg. This work will be done with the pendulums of Cambridge University which appear to have an accuracy better than $\pm$ 0.2 mgal.

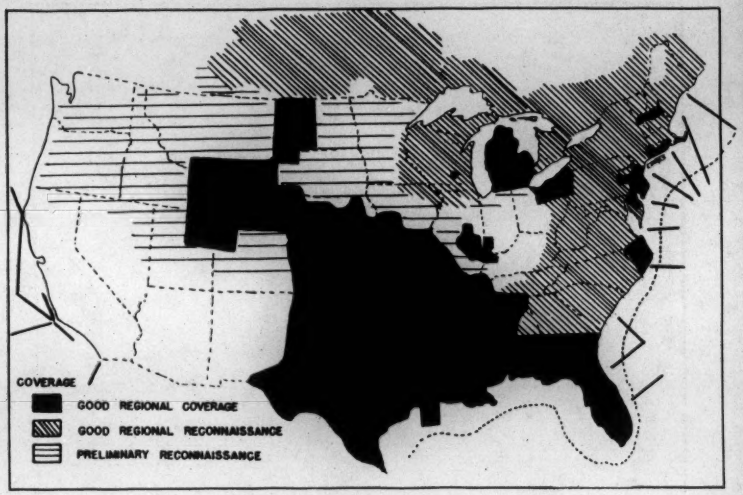


Fig. 6--Regional gravity control in the United States

Checks against the primary British pendulum stations at Cambridge, York, New Castle, and Edinburgh in 1951 by the Chairman of this Committee in connection with a new tie between Washington and Teddington using a high-range Worden meter showed an average deviation from the pendulum values of only $\pm$ 0.15 mgal.

Earth tide measurements

Although short-period Earth tide studies have been carried out by several groups in recent years, notably the Department of Terrestrial Magnetism of the Carnegie Institution of Washington, the Department of Geodesy and Geophysics of Cambridge University, and the Shell Oil Company, a more or less continuous program of such measurements has been conducted by L. B. Slichter of the Institute of Geophysics at the University of California since February 1949 using a LaCoste-Romberg gravimeter. These observations, made under contract with the Office of Naval Research, have been carried out at four locations: (1) Seismological Laboratory, California Institute of Technology, Pasadena, California; (2) University of California Campus, Los Angeles, California; (3) University of Hawaii, Honolulu, Oahu, Hawaii; and (4) Massacre Bay, Attu, Aleutian Islands.

The observations at California Institute of Technology, University of California at Los Angeles, and Hawaii were made at ten-minute intervals for approximately 45 days, and on Attu at ten-second intervals for approximately ten days. The interval of time covered on Attu Island included the total eclipse of the Sun of September 12, 1950. The instrument was in the path of totality.

Analysis of the data indicates a phase lag between the tide-inducing acceleration and the induced Earth tide for a given station. Furthermore, this phase lag may differ greatly from station to station. For example, it is about 80 minutes in Southern California and about 180 minutes at Honolulu. The ratios of the amplitudes of the accelerations due to the induced Earth tides to the amplitudes of the inducing tidal accelerations were found to be approximately the same for all stations. A program including refinement of observations and taking data at many more stations is under way at present.

Isostatic correction charts

The Isostatic Institute at Helsinki in 1947 prepared and distributed a special isostatic reduction map of the eastern half of the United States according to the Hayford-Pratt theory of isostasy for a compensation depth of 113.7 km, permitting the determination of isostatic anomalies from Bouguer values with an accuracy of one to three mgal. This year W. Heiskanen and E. Neiskonen have released a new series of similar maps for Europe based on the Airy theory of isostasy and depths of compensation of 20, 30, 40, and 60 km. Except in the more rugged regions of the Alps it is believed these maps are sufficiently accurate to permit the determination of isostatic anomalies having an accuracy of one to three mgal. This accuracy is sufficient for most purposes where isostatic anomalies are needed. The use of such maps reduces the labor of determining isostatic anomalies to a small fraction of that required for a direct calculation. The Isostatic Institute is making a notable contribution in preparing them.

Studies of the gravimetric deflection of the vertical

Gravimetric deflections of the vertical for 16 stations were computed this year on the joint program of the U. S. Coast and Geodetic Survey and the Army Map Service. Mean differences between the gravimetric and astro-geodetic deflections were 0".25 for the meridian and 0".36 for the prime vertical. Average deviations from the means were ± 0".48 and ± 0".70, respectively.

Gravity work to be published

Gravity work to be published during this coming year includes the results on the traverses made by P. C. Wuenschel of the Lamont Geological Observatory of Columbia University in 1948 between Rio de Janeiro and Buenos Aires; Buenos Aires and Cordoba, Argentina; Cordoba and Antofogasta, Chile, via Tucuman and via Valparaiso, Chile; and Antofogasta and Rio de Janeiro via La Paz. These measurements include 1863 observations made at about five-mile intervals using a high-range Frost gravimeter. It is also planned to publish the regional gravity network of the Eastern seaboard from the Maritime Province of Canada to the Gulf of Mexico established by George P. Woollard, C. L. Drake, and W. E. Bonini made under the auspices of the Geological Society of America. Approximately 6000 observations taken at about ten-mile intervals are involved in these measurements which were made for the most part with a high-range "X"-type gravity meter of the Humble Oil and Refining Company. The offshore gravity survey of the Atlantic seaboard north of Cape Hatteras made by the group at Columbia University is also expected to be published this year. These measurements include 104 measurements on seven traverses across the Continental Shelf from Nova Scotia to Cape Hatteras. Other results of interest to be published during the year are the global gravity-meter measurements in South America, Australia, and Africa.

Magnetic investigations

Regional investigations--In cooperation with the U. S. Air Force, the U. S. Coast and Geodetic Survey is conducting an airborne magnetic survey of the United States and some adjacent ocean areas. The total force and directional magnetometer developed by the Naval Ordnance Laboratory is being used on this program together with special magnetic compasses. Absolute values of D, I, H, Z, and F are being obtained.

The U. S. Geological Survey in cooperation with the U. S. Navy flew a series of total-intensity aeromagnetic profiles from Bermuda to the following points: Cape May, N. J., Argentia, Newfoundland, Halifax, N. S., Newport News, Va., San Juan, Puerto Rico, Nassau, B.W.I., Jacksonville, Fla., Wilmington, N. C., Guantanamo Bay, Puerto Rico, Puerto Plata, and Patuxent, Va. A line was also flown from Guantanamo to Kingston, Jamaica, with a return profile by way of Navassa Island. As part of the same project, a group of six lines at a spacing of approximately five miles was flown from the Ashtabula area on Lake Erie across the Appalachian Mountains to points near Ocean City, Maryland, on the Atlantic Coast and then seaward across the Continental Shelf for a distance of 300 mi. These traverses give several crossings from the Atlantic Ocean Basin on to the continent, and the results should contribute materially to the study of the nature of the transition from the continent to the ocean.

In addition to the above, the U. S. Geological Survey has built up a series of transcontinental profiles as well as several surveys of large regional extent. The location of the above and areas now being surveyed and planned to be surveyed with the airborne magnetometer are shown in Figure 7.

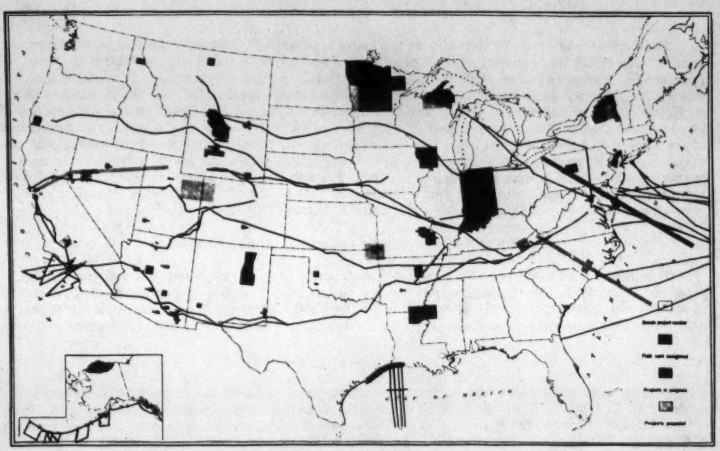


Fig. 7--Aeromagnetic projects of the Geophysics Branch, U.S. Geological Survey, January 1, 1951

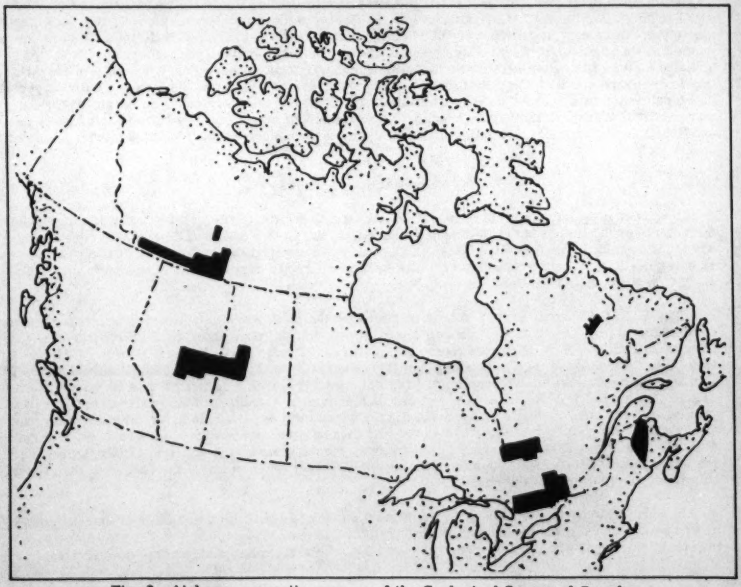


Fig. 8--Airborne magnetic surveys of the Geological Survey of Canada

Other work of a regional nature in the United States was the vertical component measurements made with an Askania magnetometer along the Alcan Highway and in Alaska by H. Drake of Harvard University as part of the gravimeter program reported. Similar measurements were also made by B. Vedeler of the University of Wisconsin in conjunction with the regional gravity survey of the northwestern part of the United States.

The Geological Survey of Canada established over 84,820 mi of airborne-magnetometer profiles covering approximately 81,685 mi of area in Canada. The Dominion Observatory program was limited to secular studies, and observations of the principal magnetic elements were made at 47 stations distributed throughout Canada. The areas covered by the Canadian aeromagnetic program to date are shown in Figure 8.

Local magnetic investigations--Local magnetometer surveys are being conducted by several university groups. At St. Louis University, C. R. Holmes is studying the magnetic field associated with igneous pipes in the Central Ozarks, and R. J. Ford, Jr. and P. E. Villars are making correlation studies of the relation of geology to electromagnetic field strengths. At the University of Wisconsin, magnetic investigations over the Baraboo syncline and the buried Waterloo Pre-Cambrian Hills are being made by N. C. Harding as part of combined seismic, gravity, and magnetic study of these structures. W. E. Bonini is making magnetic studies of the large gravitational and magnetic anomaly originating in Kansas which extends up to the Great Lakes. Daniel Linehan of Weston Observatory reports that a magnetic survey of part of Cape Code is being started to supplement seismic refraction measurements made there earlier.

Magnetic maps released--Early in 1951, the U. S. Coast and Geodetic Survey released isogonic charts for 1950 for the United States and Alaska. The world isogonic chart for 1950 compiled by the U. S. Coast and Geodetic Survey has been published by the Hydrographic Office of the U. S. Navy. In Canada, the Dominion Observatory prepared a new vertical component map this year which supplements the magnetic declination map prepared last year.

Seismic investigations

Studies of earthquakes and microseisms--Since the geographical distribution of even minor earthquake epicenters is of considerable geologic value, the map compilation of all known earthquakes in the United States that was started several years ago has been completed up to 1949 (see Fig 9). Another compilation for North America as a whole and one for the world have been started. The source of data being used are the available earthquake catalogues and the reports issued by the

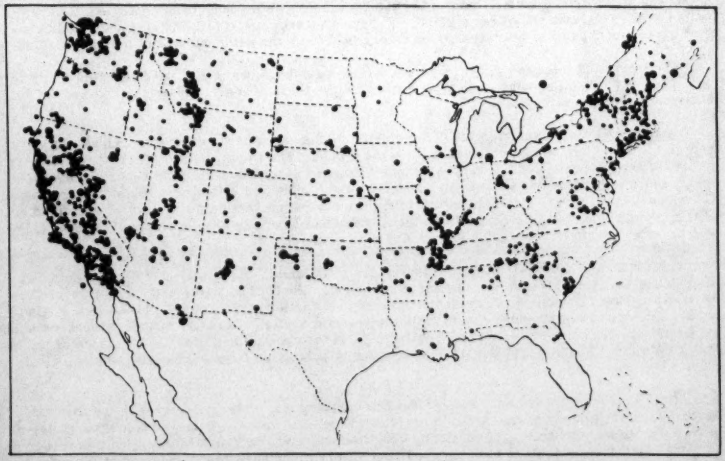


Fig. 9--Earthquake epicenters through 1948 based on reports of the U. S. Coast and Geodetic Survey

U. S. Coast and Geodetic Survey.

The seismic program of the U. S. Coast and Geodetic Survey for 1950 included studies of the relations between ocean storms and microseisms traveling across the continent, and the seasonal energy distribution of local earthquakes in the Lake Mead, Nev., area. It was found that microseisms travel without substantial energy increase along diagonal paths across the continent from Labrador to Arizona, from Labrador to Alaska, and from Alaska to South Carolina, but anomalous relations were obtained along paths going to the Pacific Coast. It was also noted that attenuation across ocean basins was higher than when traversing the continent.

Another study of considerable interest being conducted by the U. S. Coast and Geodetic Survey is the relation between earthquake intensity and distance from epicenter as a function of local geology. Characteristic smooth intensity-distance curves are being obtained for different rock types which are in agreement with the law of the conservation of energy. Another study by the U. S. Coast and Geodetic Survey is concerned with the attenuation factor of one-second transverse crustal waves as observed in the southwestern part of the United States.

At St. Louis University, under the direction of J. B. Macelwane, a study of very short-period microseisms is being made under contract with the Office of Naval Research. Other seismic studies being made at St. Louis University include a study of the relation of earthquakes in the central Mississippi Valley to regional geologic structure by R. R. Heinrich; a study of the microseismic characteristics at St. Louis in relation to positions of storms by A. T. Bingham; a study of the characteristics of seismic wave onsets from Mexico as recorded at St. Louis by D. H. Walsh; a study of the direction of faulting in western Washington as calculated from first movements in seismographs for the earthquake of April 13, 1949 by O. W. Nuttli; and a study of anomalous seismic wave propagation toward St. Louis by O. W. Nuttli.

At the University of Michigan, E. J. Moore completed a study of the structure beneath several continental and oceanic areas previously not extensively investigated using the dispersion of Rayleigh waves. One of the areas studied that is of particular interest is the Antarctic.

At the Lamont Geological Observatory of Columbia University, surface-wave studies resulted in the discovery of certain slow-speed, short-period surface waves from California earthquakes that hitherto had not been reported.

At Weston Observatory, Daniel Linehan reports that earthquake investigation of disturbances within the northeastern United States and eastern Canada (NESA) have been continued. Concentrated studies of earthquakes from 20° to 40° have also been made with the result that data concerning the mechanics of faulting may be determined from the seismograms of a single station.

The broad and intensive program of the Seismological Laboratory at the California Institute of Technology is published as a separate report in this issue of the Transactions and will not be commented on further here.

Quarry blast and other studies--The seismic studies using large explosive charges as a source of energy are being continued by several groups. The Department of Terrestrial Magnetism of the Carnegie Institution of Washington now has two sets of multiple recording equipment, and it is planned to use these to check the results obtained with single seismometers in the Chesapeake Bay region. Addftional work planned include an investigation in central Maryland east of the Appalachian Mountains, a study in the Appalachian Mountain province near Harrisburg, Pa., and some measurements in the Shield area of the Continent.

S. Katz of the Lamont Geological Observatory of Columbia University completed a seismic study based on explosive blasts of the structure beneath the Gulf of Maine and another across the Adirondack Mountain region. It is planned to extend the latter measurements to the New England coast. One result of extreme interest from the seismic studies of crustal structural makeup using surface explosive charges is that there is little corroborative evidence for the existence of the intermediate layer above the Mohorovicic discontinuity postulated from earthquake seismological studies.

At the University of Indiana, Judson Mead is carrying out, under contract with the Office of Naval Research, a study of late seismic arrivals in the near vicinity of large explosions to determine the presence or absence of vertically reflected energy from crustal discontinuities. The multiple instrument technique is being used, and observations have been conducted at quarries in Indiana, West Virginia, Tennessee, and Upper Michigan.

In Canada, the field work was completed on the seismic study of crustal structure in the Pre-Cambrian area between Kirkland Lake and Ottawa that has been sponsored by the Canadian National Research Council and carried out under the direction of John Hodgson. Seismic energy from rockbursts in the Kirkland Lake mining area was recorded at close intervals from Kirkland Lake to Timiskaming. In addition, explosive blasts from LaCave and Des Joachims were recorded at several stations and timed blasts from the Frood open pit recorded at eight stations. In all, 115 stations were occupied along the traverse and the data are now being analyzed. A similar study is being planned for British Columbia using a tripartite station network and the numerous earthquakes in the area as a source of energy.

Regional seismic studies of the buried Pre-Cambrian crystalline complex were continued this year by the Lamont Geological Observatory of Columbia University in the Atlantic Coastal Plain and Continental Shelf area. Three profiles were established across Long Island Sound and two profiles across the Shelf Area. One of the latter extends out from Block Island and the other from Shinnecock Inlet on Long Island. The development of seismic refraction measurements in the Atlantic Coastal Area to date is shown in Figure 10. Similar offshore surveys along the California Coast have also been started by R. Raitt of the Marine Physical Laboratory at San Diego. In Wisconsin a program of mapping the pre-glacial and Pre-Cambrian buried surfaces has been started under the direction of G. P. Woollard at the University of Wisconsin using the seismic refraction method.

Local seismic studies--Although local shallow-depth seismic studies, such as those made in connection with ground-water supplies and engineering and mining investigations, contribute little basic geologic knowledge in many areas, they contribute a lot of fundamental knowledge in areas covered by glacial drift both as to the nature and depth of bedrock and the types and ages of till present. In many areas where there has been no systematic preservation of well data, seismic data are becoming the primary source of subsurface information.

J. Mead of the University of Indiana reports several investigations in Indiana ranging from studies of variation in thickness of glacial drift to subsurface mapping of horizons beneath the pre-glacial surface. Using the portable 12-channel refraction equipment developed by the Century Geophysical Company, over 500 depth determinations were made. Similar equipment was also employed on several investigations in connection with ground-water studies in Wisconsin by personnel of the Department of Geology of the University of Wisconsin, in Missouri by Leroy Sharon of Washington University, and in New Hampshire, Massachusetts, Vermont, Connecticut, and New Jersey by personnel of Weston Observatory, and is also now being used by the U. S. Geological Survey. In connection with the proposed Nyack Bridge across the Hudson River, personnel of the

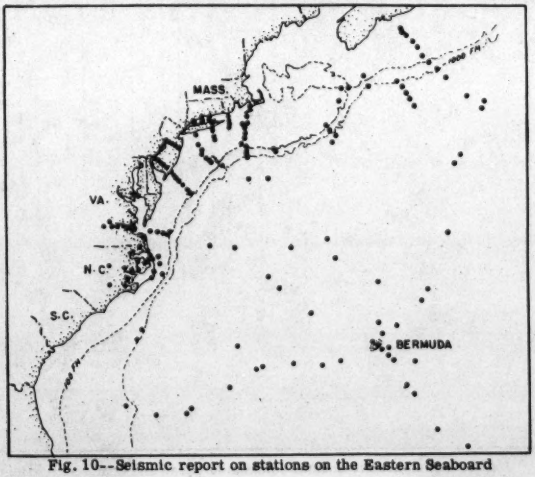


Fig. 10--Seismic report on stations on the Eastern Seaboard

Lamont Geological Observatory of Columbia University made an extensive seismic survey and study of the geologic structure beneath the river and found a buried former gorge of the river over 600 ft deep.

Engineering seismic studies were also carried out by personnel of Weston Observatory in cooperation with the Department of Public Works of Massachusetts, the U. S. Geological Survey, and the Department of Public Works of California. At St. Louis University, studies on the differentiation of dolomites by means of seismic wave velocities were made by C. Kisslinger; and subsurface mapping of bedrock topography was carried out in the Missouri River flood plain by L. L. Oriard and in the American Bottoms of Illinois by J. A. Fava, G. P. Jones, Jr., and G. E. Haines. Similar measurements were also conducted by personnel of the Geology Department of the University of Wisconsin in Minnesota, Wisconsin, and the Upper Michigan peninsula.

Earthquake observatories--Three new and reactivated seismological observatories were reported during the year. They are at the University of Wisconsin, at Resolute Bay on Cornwallis Island, Northwest Territories, and at Halifax, Nova Scotia.

Changes in crustal structure at the continental margins--The seismic work in the deep ocean basins being made under contract with the Office of Naval Research by Maurice Ewing of Columbia University in the Atlantic Ocean and by R. Raitt of the Marine Physical Laboratory in the Pacific Ocean have brought out significant differences between the crustal structure of the continents and

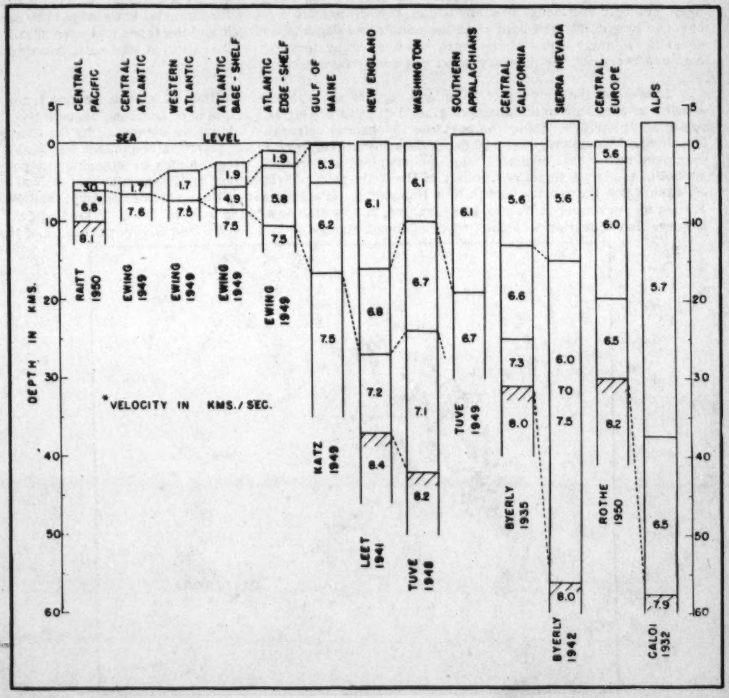


Fig. 11--Comparative coastal columns in ocean and continental areas

the ocean basins. On the basis of these and other measurements a section has been prepared summarizing available information on differences in crustal structure in the oceans and continents. This is shown in Figure 11.

Radioactive and thermal investigations

At the Massachusetts Institute of Technology, P. M. Hurley working under contract with the Office of Naval Research has made a considerable number of radioactive age determinations on zircon and sphene using the helium method to see if these accessory minerals can be used for determining the age of ordinary granites. Although such measurements are handicapped by the fact that the alpha-particle ranges are of almost the same magnitudes as the crystal dimensions making it necessary to size the crystals and measure the alpha emission to determine the ratio of alpha particles remaining in the crystal, the preliminary results indicate fairly close agreement with known geologic ages. The program of measuring radioactive heat production in rocks is continuing, and with the installation of new equipment the work will be extended to include ultramafic rocks and meteorites.

At the Lamont Geological Observatory of Columbia University, the group working under the direction of J. L. Kulp have developed a satisfactory low-level scintillation alpha counter which is being used to study deep-sea cores and rock specimens. The cores are also being studied by the radon-ionium method. Apparatus for the determination of natural radiocarbon has been completed and is being applied to the study of deep-sea cores, carbonate from deep ocean water, Pleistocene glacial samples, and related materials. Work is continuing on the strontium isotope ratio method of age determination.

At the University of Toronto a mass spectrometer has been completed for use in age determinations by measurements of lead isotope ratios. Field Geiger equipment and scintillation counters have been developed and were used extensively last summer. The heat-flow measurements in 11 Ontario and Quebec mines by A. D. Misener were completed and are now being analyzed.

At Harvard University, Francis Birch reports that thermal-conductivity measurements have been completed for samples of rock from the Homestake Mine in the Black Hills of South Dakota, and that heat-flow determinations are to be made.

As part of the program of measurements carried out by the Scripps Institution of Oceanography this past summer in the Pacific Ocean, R. Revelle reports thermal-conductivity and heat-flow measurements were made along the track followed from San Diego to the Hawaiian Islands and Bikini Atoll.

Geologic investigations

A concerted attack on some of the major problems of Appalachian structural geology is in progress in the State of New York and detailed systematic geologic mapping of several quadrangles is being carried out by several investigators including E. B. Knopf, Scott Warthin, W. H. Bucher, and John Weaver. Areas mapped or in progress of being mapped include the Millbrook, Copake, Kinderhook, Poughkeepsie, and Rhinebeck quadrangles. It is hoped that geophysical work can be carried out in these same areas to supplement the geologic investigations.

Studies of the deep drilling cores taken from Bikini in 1947 and from Funafuti in 1898 to 1902 are now being made under the direction of H. S. Ladd of the U. S. Geological Survey with the assistance of J. I. Tracey of the U. S. Geological Survey and Gordon Lill of the Office of Naval Research. In addition to this work, more core material is expected to become available soon from recent drilling in the northern Marshall Islands. It is expected that these studies will furnish a considerable amount of new information bearing upon oceanic islands.

Department of Geology (G.P.W.),
University of Wisconsin,
Madison, Wisconsin

(Communicated manuscript received May 2, 1951;
open for formal discussion until January 1, 1952.)

APPENDIX 4--REPORT OF THE SPECIAL COMMITTEE ON COSMIC-TERRESTRIAL RELATIONSHIPS FOR THE YEAR ENDING JUNE 30, 1951

Harlan T. Stetson, Chairman
Edward O. Hulburt, Vice Chairman

Horace R. Byers — Robert R. McMath
Ross Gunn — George P. Woollard

The Special Committee on Cosmic-Terrestrial Relationships for the triennium 1950-1953 has been active during the year in the several fields which it is the object of the Committee to promote. In view of the impending triennial meeting of I.U.G.G. in Brussels in August 1951, the Committee thought it desirable to solicit from a number of workers in related fields brief abstracts of recent research of cosmic-terrestrial interest in this country. In soliciting such abstracts from various institutions and individual workers, a breakdown of subject matter was suggested to include the following topics: (a) Solar activity, including photospheric and related phenomena; (b) ultraviolet radiation and coronal-line intensities with related terrestrial effects, such as auroral displays, ionization of the Earth's upper atmosphere, and possible cosmic-ray variations; (c) meteorological phenomena as related to solar activity; and (d) ionospheric and tropospheric effects, cosmic radiation of radio frequencies.

The new field of radio astronomy which definitely bears on the subject of cosmic-terrestrial relationships is attracting increasing attention and a considerable number of recent contributions have come from this field.

The following titles and abstracts have been received:

BROXON, J. W., University of Colorado, Cosmic-ray bursts, Phys. Rev., v. 81, p. 555, 1950.

EVANS, J. W., C. S. YU, and B. WHITE, High Altitude Observatory, Boulder, Colorado, Solar-flare observations, to be published.

FRIEDMAN, H., S. W. LICHTMAN, and E. T. BYRAM, Naval Research Laboratory, Measurement of solar X-rays and extreme ultraviolet with rocket-borne photon counters, to be published in J. Geophys. Res.

GARTLEIN, C. W., and R. K. MOORE, Cornell University, Southern extent of Aurora Borealis in North America, J. Geophys. Res., v. 56, pp. 85-96, 1950.

HAGEN, J. P., Naval Research Laboratory, Temperature gradients of the Sun's atmosphere, Astrophys. J., May 1951.

HAGEN, J. P., F. T. HADDOCK, and G. REBER, Naval Research Laboratory and National Bureau of Standards, NRL Aleutian eclipse expedition, Sky and Tel., v. 10, March 1951.

HAVENS, R. G., Naval Research Laboratory, Measurements with rockets of pressures, densities, and temperatures up to 160 kilometers, to be published in J. Geophys. Res.

KORFF, S. A., New York University, New information regarding Sun's magnetic field from cosmic-ray neutron studies, to be published.

MAPLE, E., W. A. BOWEN, and S. F. SINGER, Naval Ordnance Laboratory and Applied Physics Laboratory, Rocket measurements of magnetic fields of ionosphere currents near the magnetic equator off coast of Peru, to be published.

MEINEL, A. B., Yerkes Observatory, Upper atmosphere research at Yerkes Observatory during 1950, Astrophys. J., v. 113, p. 50, 1951, v. 111, p. 555, 1950, and J. Geophys. Res., v. 55, p. 301, 1950.

MENZEL, D. H., Harvard University, Theory of solar effects of magnetic and ionospheric storms and aurorae, to be published.

MOORE, R. K., Cornell University, A V.H.F. propagation phenomenon associated with the aurora, J. Geophys. Res., v. 56, pp. 97-106, 1951.

POMERANTZ, M. A., Bartol Foundation, An increase in the primary cosmic-ray intensity following a solar flare, Phys. Rev., v. 81, p. 731, 1951.

ROBERTS, W. O., D. E. TROTTER, B. WITTE, and W. N. FLEMING, High Altitude Observatory, Boulder, Colorado, Heliographic maps of coronal activity, Sudden ionospheric disturbances without solar flares, to be published.

SEEGER, C. L., and R. E. WILLIAMSON, Cornell University, Radio pole of the galaxy at 205 Mc, Observations of the variable 205-Mc radiation of Cygnus A, to be published.

TOUSEY, R., F. S. JOHNSON, J. D. PURCELL, and K. WATANABE, Naval Research Laboratory, Vertical distribution of ozone, Intensity distribution in the ultraviolet spectrum of the Sun, Direct measurements of solar extreme ultraviolet and X-rays from rockets by means of a Ca SO_4 Mn phosphor. to be published.

WAYNICK, A. H., Pennsylvania State College, Studies of ionosphere using very-long wave pulse techniques, to be published.

WHIPPLE, F. L., Harvard University, Theory of micro-meteorites, Comets and the zodiacal light, Comets, meteors, and the inter-planetary complex, Harvard College Observatory abstracts.

A ten-year series of field-intensity measurements of the National Bureau of Standards' standard frequency signal at five megacycles, made at the Cosmic-Terrestrial Research Laboratory at Needham, Massachusetts, has been analyzed throughout the 24-hour day over the period, yielding the following deductions:

(1) Rising fields occurred during the night hours from sunspot minimum to sunspot maximum, the greatest rise, approximately tenfold, occurring during the midnight hour.

(2) Falling fields occurred during daytime hours from sunspot minimum to sunspot maximum, with the greatest change taking place near the noon hour where the values at sunspot maximum attained only five per cent of the noon fields experienced at sunspot minimum.

(3) Field intensities throughout the solar cycle were most nearly independent of sunspots during the hour around sunrise and the hour following sunset.

Robert R. McMath, in cooperation with H. W. Dodson--At the McMath-Hulbert Observatory of the University of Michigan there is a program of observation and analysis of the solar spectrum with high dispersion. The work covers both the photographic and infra-red regions of the spectrum and deals with spectra of detailed features of the Sun such as the limb, prominences, and flares, as well as the fundamental solar spectrum. A photometric atlas of the near infra-red solar spectrum, 8465 to 25,242, has recently been published.

Continuous, monochromatic, photographic records of rapidly changing solar activity form part of the regular program of the Observatory. These spectro-heliographic studies show the development on the disk of large sunspot regions, the outbreak of flares, and active dark flocculi. Solar-limb photographs record prominence motions and include simultaneous spectrographic records in the neighborhood of H_α.

Charts containing solar, ionospheric, and geomagnetic data for the past three years have been compiled. Photometric light curves of flares provide quantitative data of value in efforts to distinguish between solar activity with terrestrial effects and that with none. Solar-noise records at 200 Mc/s secured at Cornell and intercomparison of limb and disk activity provide further data for identification of the active solar regions associated with terrestrial disturbances.

Charles F. Brooks--The solar work at the Blue Hill Meteorological Observatory (BHO) of Harvard University continued jointly with the U. S. Weather Bureau (USWB) through 1950, essentially as in the past, using Eppley pyrheliometers and tube, and Micromax (galvanometric) or Brown (electronic) recording potentiometers. The following insolation observations have been made: (a) Total of direct and diffuse solar radiation on a horizontal surface (by BHO, 1932-1948, and USWB since 1948); (b) insolation on a vertical surface facing south (USWB since 1945); (c) insolation on a vertical surface facing north (USWB since 1949); (d) intensity of the solar beam at normal incidence (BHO since 1932), which is checked a few times monthly by Smithsonian silver disk pyrheliometer; (e) duration of intensity at normal incidence in excess of 0.3 Langleys/min (BHO, daily by counter since 1949, and by trace burnt on a card by the focussed rays of the Sun, by Campbell-Stokes sunshine duration recorder since 1896); (f) diffuse insolation on a horizontal surface (USWB since 1945), not yet published though studies by both USWB and BHO were in progress.

I. F. Hand, Meteorologist in Charge of the Weather Bureau's Solar-Radiation Field Testing Unit at Blue Hill, visited 97 solar stations, more than 50 of which are new installations. The majority of the stations visited were Weather Bureau stations, but also visited were 24 University stations, three Canadian meteorological stations (Edmonton, Winnipeg, and Toronto), and one Mexican station (Tacubaya, Mexico City). Seven of the new stations installed were cooperative stations and the remainder were Weather Bureau stations. At the present time (February 1951) solar records from 67 stations are being published. When all the new stations are activated, more than 90 will be publishing data on insolation on a horizontal surface, and a few will be publishing data on the intensity of the direct solar beam at normal incidence. At present, the insolation on vertical surfaces and the diffuse insolation are recorded only at Blue Hill.

During the past two or three years meteorologists have evinced renewed interest in relating atmospheric processes to extra-terrestrial influences developed. Along with a new understanding of the large-scale action of the atmosphere, meteorologists arrived at new concepts of the role of solar variability in explaining past climatic changes and irregular variations in the general circulation of the atmosphere.

One of the most stimulating papers to emerge was that of B. and G. Duell entitled, The behavior of barometric pressure during and after solar particle invasions and solar ultraviolet invations [Smithsonian Misc. Collections, v. 110, no. 8, 1948]. The authors investigated the short-range disturbing effects of sudden solar outbursts, considering in turn sudden particle invasions of the atmosphere from the M-regions of the Sun and sudden strong ultraviolet invasions of the atmosphere resulting from bright chromospheric eruptions. They found that the day-to-day changes in the sea-level pressure reflect these invasions, at least during the winter season and during years of low sunspot activity.

Taking 320 days selected independently as having the highest geomagnetic disturbances (particle invasions) in winter for years with sunspot number less than 40, the Duells found a significant pattern of sea-level pressure departure from normal on days immediately following the disturbance. Over Europe a minimum of pressure occurred on the third or fourth day following the invasion date. Using the occurrence of bright chromospheric eruptions as an index of ultraviolet invasion, the authors found that the ultraviolet maximum produced a positive pressure anomaly instead of negative as in the case of the particle invasions. The pressure maximum was reached on the fourth or fifth day after the invasion.

A related paper, making extensive use of the results of the Duells, was written by H. C. Willett for the Ahlmann volume, Glaciers and Climate, published in Sweden, entitled, Solar variability as a factor in the fluctuations of climate during geological time [Geografiska Annaler, Ahlmann Volume, pp. 295-315, 1949]. In this paper Willett examined the principal theories currently accepted to account for fluctuations of past climates between glacial and inter-glacial extremes. Solar variability was emphasized as an acceptable hypothesis, particularly the irregular solar variability which characterizes the sunspot cycle. He found that the change in mean winter pressure from sunspot minimum to the following major sunspot maximum resulted in a pattern for Europe and the North Atlantic very similar to that found by the Duells for particle-invasion conditions.

The data showed that the winter pressure change from the sunspot minimum to the following minor sunspot maximum was the reverse, that is, strongly positive in western Europe. The distribution of precipitation was fairly sensitive to the pressure changes, the temperatures less so. The importance of heavy precipitation in high latitudes in periods of glacial formation was suggested.

At the Twenty-Ninth Annual Meeting of the American Geophysical Union in Washington, Willett presented a paper entitled, Patterns of world weather changes [Trans. Amer. Geophys. Union, v. 29, pp. 803-809, 1948]. After examining discouraging results of statistical studies of correlations among features of the general circulation, the author suggests the possibility of direct solar influence on the short-period irregular changes of the gneeral circulation. It is shown that causes of past changes have operated in the same sense over the whole world, not just over one hemisphere, and the conclusion is drawn: "Variable solar activity, particularly in the shorter ultraviolet wave lengths, such as almost certainly accompanies the sunspot cycle, is the most logical and easily postulated physical control factor which might be made to account for the secular, the climatic, and the geological variations of the mean state of the general circulation."

Willett, in a later paper entitled, Long-period fluctuations of the general circulation of the atmosphere [J. Met., v. 6, pp. 34-50, 1949], summarized the facts and theories concerning climatic variations during observational time. The following is quoted from his abstract: "The essential similarity of the changes of climate during postglacial time as intermediate between the geological changes on the one hand and the secular changes on the other is attributed to the basic change of the general circulation pattern which evidently characterizes all of these climatic variations. The basic change apparently consists essentially of a contraction or expansion of the circumpolar zonal weather pattern, accompanied by decrease and increase, respectively, of cyclonic activity in the low-pressure belts. It is emphasized that solar variability of the sunspot variety is the only possible single factor of climatic control which might be made to account for all of these variations."

Finally, in two 1951 papers, Temperature trends of the past century [R. Met. Soc., Centenary Proc., pp. 195-206, 1951] and Extrapolation of sunspot-climate relationships [J. Met., v. 8, pp. 1-6, 1951], Willett's ideas appear to have crystallized. In the most recent paper, he calls attention to some striking facts concerning the cyclical variation of sunspots and certain elements of the climatic variations of the Northern Hemisphere during the past two centuries. After noting the tendency for concurrence or succession of such elements as precipitation, temperature, glaciation, storm tracks, circumpolar atmospheric vertex, and lake levels, all in relation to sunspot activity, Willett undertakes an extrapolation forecast. The extrapolation indicates a falling tem-

perature over the world for the next 15 years, but no indication of a long trend in this direction. Rainfall south of 50° N would be expected to be higher in the next 20 years, with increasing lake levels. It is indicated that the general recent recession of the glaciers is due to be reversed in the very near future.

In an article on the circulation of the atmosphere by C. G. Rossby and H. C. Willett entitled, The circulation of the upper troposphere and lower stratosphere [Science, v. 108, pp. 643-652, 1948], the development of a concentrated zone of very strong westerly winds in the high troposphere, now familiarly known as the "jet stream," was discussed. Rossby had presented ideas concerning this phenomenon on the Earth and other planets at the Fiftieth Anniversary Symposium of the Yerkes Observatory in September 1947. This was later published [G. P. Kuiper, ed., The atmospheres of the Earth and planets, Univ. of Chicago Press, 1949].

Rossby's initial publication, however, was in two 1947 papers, one entitled, On the distribution of angular velocity in gaseous envelopes under the influence of large-scale horizontal mixing processes [Bull. Amer. Met. Soc., v. 28, pp. 53-68, 1947], and the other by Staff Members of the Department of Meteorology of the University of Chicago entitled, On the general circulation of the atmosphere in middle latitudes [Bull. Amer. Met. Soc., v. 28, pp. 255-280, 1947]. Basically, the Rossby theory predicts that in a thin hemispherical shell on a rotating globe, corresponding to a planetary or stellar atmosphere, lateral mixing would cause the value of the vertical component of absolute vorticity at the pole to be preserved from the pole to a certain middle latitude. Equatorward from this latitude the vorticity would have imparted to it a distribution characteristic of transfer by lateral mixing. The profile obtained agrees with that observed in the Earth's atmosphere and also in the atmosphere of the Sun. Atmospheric effects in some of the major planets appeared to be in agreement with the theory.

In treating the jet stream and its role in the general circulation, Willett, in the article in Science referred to above, states: "Particularly in connection with the double sunspot cycle, there is considerable statistical and synoptic evidence of a definite influence of irregular solar variability on the index characteristics of the general circulation pattern. The inference is made that irregular solar activity may be a controlling factor in all of the extensive long-period fluctuations of the general circulation."

Another paper of basic interest by R. A. Craig entitled, The observations and photochemistry of atmospheric ozone and their meteorological significance [Amer. Met. Soc., Met. Monographs, v. 1, no. 2, 1950], should be mentioned because of the important extra-terrestrial influences operating on the ozone layers. For the purpose of this report, Craig's most interesting conclusion is that ". . . the seasonal and latitudinal variations of ozone are attributed largely to horizontal or vertical circulations in the lower part of the stratosphere. Seasonal and latitudinal variations of zenith angle and of temperature must also have some effect. The day-to-day variations of ozone are discussed and it is concluded that they imply extensive vertical motions and convergence in the stratosphere, since advection cannot explain many of their features. The observed vertical distributions of ozone fit well with the above ideas. Finally, it is pointed out that solar effects on the ozone layer are not apt to be indicated by total amounts of ozone."

541 Lido Drive (H.T.S.),
Fort Lauderdale, Florida

(Communicated manuscript received May 7, 1951;
open for formal discussion until January 1, 1952.)

SPECIAL ANNOUNCEMENTS

Thirty-Third Annual Meeting, Washington, D. C., May 5-7, 1952--Attention is called to the preliminary announcement in the June issue of the Transactions giving the dates of the Thirty-Third Annual Meeting, as shown above. A more complete announcement will appear in the October issue. In the meantime, be making your plans for participation in the meeting.

Meeting of the International Union of Geodesy and Geophysics--The Ninth General Assembly of the International Union of Geodesy and Geophysics is to be held in Brussels, Belgium, August 21 to September 1, 1951. As we go to press, there are indications that the group from the United States, including guests, will exceed 100. It is planned that a preliminary report of the meeting will appear in the October issue of the Transactions.

Designation of Vice President, Section of Hydrology--In accordance with the Statutes, Walter B. Langbein has been designated as Vice President of the Section of Hydrology by the Executive Committee of the Section to fill the unexpired term of the late Merrill Bernard.

GEOPHYSICAL RESEARCH CORPORATION

Geophysical Prospecting
Application of Geophysical Methods in the Petroleum Industry

2607 North Boston Place
Tulsa 6, Oklahoma

GULF RESEARCH & DEVELOPMENT COMPANY
GULF OIL CORPORATION

Geophysical and Other Research
Relating to the Petroleum Industry

P. O. Drawer 2038
Pittsburgh 30, Pennsylvania

INSTITUTE OF GEOPHYSICS

UNIVERSITY OF CALIFORNIA

Los Angeles 24, California

RANNEY METHOD WATER SUPPLIES, INC.

Ground Water Exploration and Development

841 Alton Avenue
Columbus 3, Ohio

RUSKA INSTRUMENT CORPORATION

Developers, Designers, and Manufacturers of Instruments for Field and Observatory Use
Magnetic, Geodetic, Seismic, and Meteorological Work

4607 Montrose Boulevard
Houston 6, Texas

SEISMOGRAPH SERVICE CORPORATION

Seismic Exploration Service for
Oil and Gas Structures throughout the World

P. O. Box 1590
Kennedy Building
Tulsa 1, Oklahoma

SPRENGNETHER INSTRUMENT COMPANY

Manufacturer of Seismological and Geophysical Instruments
Instrumental Development and Research

4567 Swan Avenue
St. Louis 10, Missouri

TRANSACTIONS
AMERICAN GEOPHYSICAL UNION

Volume 32 OCTOBER 1951 Number 5

DETERMINATION OF FLOWS IN INTERCONNECTED ESTUARINE CHANNELS PRODUCED BY THE COMBINED EFFECTS OF TIDAL FLUCTUATIONS AND GRAVITY FLOWS

Francis E. Swain

Abstract--A method is presented for determining the variable flows produced in an estuarine channel system by gravity flows from the uplands and the effects of tidal heights and phases throughout the system. The procedure makes use of a theory developed to establish the magnitude of "surge" or "bore" waves produced in canals by a disturbance of flow. The tidal height variations are represented as a series of incremental changes in water surface height which in turn produce small bore waves. The effect of channel friction, length, and cross-section are taken into account. A suggested procedure for solving a given problem is presented together with an illustrative example which gives the results of a study made for the delta region of the Sacramento and San Joaquin Rivers in central California.

Introduction

The outflow of a river that enters a tidal sea is generally dominated for a considerable distance upstream from the mouth by the reversing currents caused by the alternate filling and emptying action of the tidal fluctuations. The time variation of flows in a system of interconnected estuarine channels depends upon the normal gravity flow of water into these channels from the uplands and the effects of the tidal heights and phases throughout the system.

In the following discussion there is presented a method for determining the variable flows in an estuarine channel system. The procedure makes use of a theory developed to establish the magnitude of "surge" or "bore" waves produced in canals by a disturbance of flow. It has been noted [PILLSBURY, 1940, pp. 1-75 and 227-249] that the rate at which high and low water, as well as the strength and turn of the current, advance along an estuary is often so close to the rate of advance of a frictionless progressive wave in a channel of uniform dimensions that this value is frequently taken as the normal rate of progress of the tide. This fact suggests the use of the bore or surge wave theory in the analysis of estuarine channel flows since the tidal variations may be represented as a series of small incremental changes in the height of the water surface which in turn produce small bore waves. With the tidal variations at a given location in the interconnected system known, preferably at a downstream point in the system, the tidal variations at other points may be determined. The effects of friction, channel cross section, and channel length may be taken into account.

The friction effects are treated individually in each separate channel by assuming the entire friction to be concentrated at a barrier at some section in the channel, usually at the mid-length of the reach. The combinations and reflections of the several individual waves arriving at a junction of two or more channels of the same or different cross section are treated in a manner similar to that employed in the theory of water hammer for branch connections.

The resultant flows produced by the combined action of the tides and gravity are determined by computing the flows due to gravity alone initially and superimposing the flows produced by the tidal fluctuations. The gravity flows represent, essentially, initial conditions from which the combined analysis proceeds. The initial flows are determined by a gravity network analysis, using standard procedures [CROSS, 1936].

Derivations of the various formulas for wave heights and velocities at friction barriers and channel junctions are presented in the following section. An illustrative example, which demonstrates the application of the theory to a specific problem, is given in a section following the theoretical development.

Assumptions--The following assumptions have been made in the analysis: (a) The channel is of constant cross section throughout its entire length. (b) The entire friction effects in the channel are concentrated at one cross section; namely, the friction barrier. (c) The mean depth d_m of the water in the channel is equal to the area A of a vertical cross section of the water prism

divided by the corresponding top width of the water surface. (d) Incoming wave heights from either end of the channel arrive at the friction barrier at the same instant. (e) The bore waves travel along the water surface of the channel with a celerity $a = \sqrt{gd_m}$. (f) Height h of surge wave is small compared to mean depth d_m of water in channel.

Notation--The following notation has been used in the study:

a = celerity of wave with respect to undisturbed water ahead of the wave, ft/sec
A = area of vertical cross section of water in channel, sq ft
d_m = mean depth of water in channel, ft
g = acceleration of gravity, ft/sec^2
h = height of surge or bore wave, ft
K = friction factor whose magnitude is such that KV^2 represents the friction loss in the entire length of channel when the flow has a velocity V, sec^2/ft
Q = flow in channel, cu ft/sec
V = velocity of water in channel at the barrier after the arrival of the bore waves at the barrier, positive as shown in Figure 2, ft/sec
V_0 = initial velocity of water in channel at the barrier, positive as shown in Figure 1, ft/sec
V_1 = velocity of water in channel associated with the depth including wave of height y_1, positive when toward the barrier, as shown in Figure 1, ft/sec
V_2 = velocity of water in channel associated with the depth which includes the wave of height y_2, positive when toward the barrier, as shown in Figure 1, ft/sec
y = height of principal lunar component of tide, ft (see Fig. 16)
y_0 = initial height of water surface on the upstream side of the barrier when V_0 is positive, measured positively above an arbitrary datum before the arrival of the incoming bore waves, as shown in Figure 1, ft
y_1 = height of incoming bore wave which approaches the barrier from the upstream side when V_0 is positive, measured positively above the level existing ahead of the wave, as shown in Figure 1, ft
y_2 = height of incoming bore wave which approaches the barrier from the downstream side when V_0 is positive, measured positively above the level existing ahead of the wave, as shown in Figure 1, ft
y_A = height of water surface on upstream side of barrier when V_0 is positive after reflection of incoming bore waves from barrier, measured positively above the arbitrary datum, as shown in Figure 2, ft
y_B = height of water surface on downstream side of barrier when V_0 is positive after reflection of incoming bore waves from barrier, measured positively above the arbitrary datum, as shown in Figure 2, ft
$\lambda = a/g$

Development of formulas for wave heights and velocities at friction barrier in channel

As noted in the introduction, it is convenient to account for the effects of friction along the length of a channel by assuming all of the friction to be concentrated at a barrier at a chosen location in the channel. It is usually expedient to place the barrier at the midpoint of the channel length to facilitate the computations of wave heights or tidal fluctuations at each end of the reach.

Mathematical development--If water flowing in a channel with a velocity V is instantly checked, a wave of approximate height

$$h = aV/g \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

is produced [ROUSE, 1938, chap. 16, pp. 377-402].

For $V_0 > 0$, $V > 0$, consider the conditions shown in Figure 1 which represent those existing at a friction barrier before the arrival of the incoming bore waves from the opposite ends of the channel. The water level on the upstream or A side of the barrier will be higher than that on the downstream or B side by the amount of the actual friction loss in the entire channel, KV_0^2, assumed to be concentrated at the barrier. A wave of height y_1 approaches the barrier from the upstream side leaving behind it a total depth of $y_0 + y_1$ above the arbitrary datum and a resultant velocity V_1. Similarly, a wave of height y_2 approaches the barrier from the downstream side, leaving behind it a total depth of $y_0 - KV_0^2 + y_2$ above the arbitrary datum and a resultant velocity of V_2.

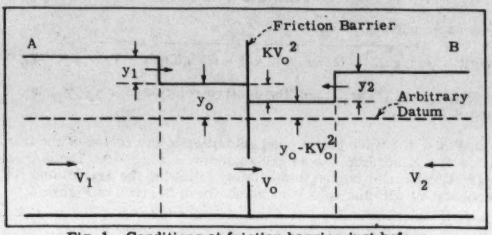


Fig. 1--Conditions at friction barrier just before arrival of waves for $V_0 > 0, V > 0$

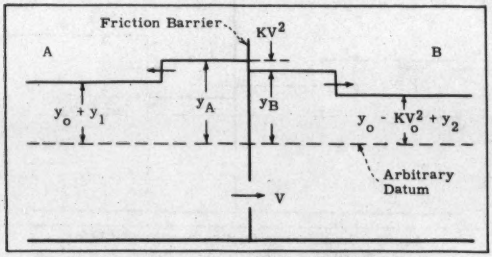


Fig. 2--Conditions at friction barrier immediately after arrival and reflection of waves for $V_0 > 0, V > 0$

After the incoming waves of heights y_1 and y_2 have struck and are partially reflected from the barrier, the water surface levels on opposite sides of the barrier will be changed from their previous values, causing a new velocity V to be established through the barrier. A diagram showing conditions at the friction barrier immediately after the arrival and reflection of the waves is given in Figure 2.

The resultant height y_A of the water surface level on the upstream side of the friction barrier is equal to the sum of the original water surface height y_0, the height y_1 of the incoming wave, and the height of the reflected portion of the incoming wave which is equal to $y_1 - (a/g)(V - V_0)$. Expressed mathematically this relation is

$$y_A = y_0 + 2y_1 - (a/g)(V - V_0) \qquad V_0 > 0, V > 0 \quad \ldots\ldots\ldots\ldots (2)$$

The resultant height y_B of the water surface level on the downstream side of the friction barrier is determined similarly to be

$$y_B = y_0 - KV_0^2 + 2y_2 + (a/g)(V - V_0) \qquad V_0 > 0, V > 0 \quad \ldots\ldots\ldots\ldots (3)$$

Upon inspection of Figure 2, we may write

$$y_A - KV^2 = y_B \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

After substituting (2) and (3) into (4), we obtain

$$V^2 + (2a/gK)V - (2/K)(y_1 - y_2) - (2a/gK)V_0 - V_0^2 = 0 \quad \ldots\ldots\ldots\ldots (5)$$

Solving for V, we have

$$V = -a/gK \pm \sqrt{a^2/g^2K^2 + (2/K)(y_1 - y_2) + (2a/gK)V_0 + V_0^2} \quad \ldots\ldots\ldots\ldots (6)$$

The initial and boundary conditions of the problem require that V and V_0 be positive quantities.

The desired expression for V is

$$V = -a/gK + \sqrt{a^2/g^2K^2 + (2/K)(y_1 - y_2) + (2a/gK)V_0 + V_0^2} \qquad V_0 > 0, V > 0 \ldots . (7)$$

Equations (2), (3), and (7) are, then, the desired relations for y_A, y_B, and V, respectively, when $V_0 > 0$ and $V > 0$.

For $V_0 > 0$, $V < 0$, the wave heights and velocities in the region of the friction barrier just before the arrival of the incoming waves are as shown in Figure 3. The diagram of the conditions existing in the friction barrier region immediately following the arrival and reflection of the incoming waves consistent with the velocities noted above is given in Figure 4.

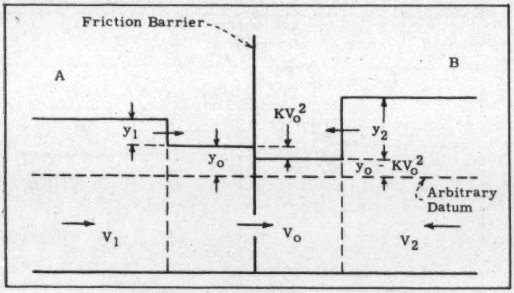


Fig. 3--Conditions at friction barrier just before arrival of waves for $V_0 > 0$, $V < 0$

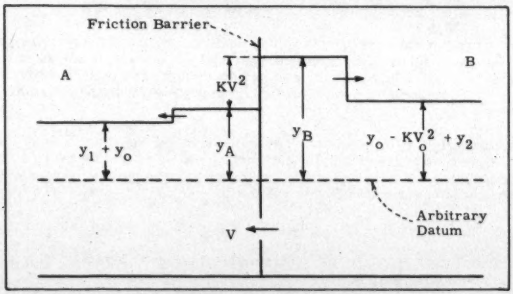


Fig. 4--Conditions at friction barrier immediately after arrival and reflection of waves for $V_0 > 0$, $V < 0$

As before, the height y_A of the water surface on the A side of the friction barrier may be determined in terms of the various velocities and depths in the channel. Thus

$$y_A = y_0 + 2y_1 - (a/g)(V - V_0) \qquad V_0 > 0, V < 0 \ldots . (8)$$

Similarly, the height y_B may be determined in terms of the same quantities.

$$y_B = y_0 - KV_0^2 + 2y_2 + (a/g)(V - V_0) \qquad V_0 > 0, V < 0 \ldots . (9)$$

From inspection of Figure 4, we note that

$$y_B = y_A + KV^2 \qquad (10)$$

After substituting (8) and (9) into (10), we obtain

$$V^2 - (2a/gK)\,V + (2/K)\,(y_1 - y_2) + (2a/gK)\,V_0 + V_0^2 = 0 \quad \ldots\ldots\ldots\ldots (11)$$

Solving for V, we obtain

$$V = a/gK \pm \sqrt{a^2/g^2K^2 - (2/K)\,(y_1 - y_2) - (2a/gK)\,V_0 - V_0^2} \quad \ldots\ldots\ldots\ldots (12)$$

The initial and boundary conditions require that V_0 be a positive quantity and V a negative quantity. Consistent with the requirements, we obtain

$$V = (a/gK) - \sqrt{a^2/g^2K^2 - (2/K)\,(y_1 - y_2) - (2a/gK)\,V_0 - V_0^2} \qquad V_0 > 0,\ V < 0 \ldots\ldots (13)$$

Equations (8), (9), and (13) are, then, the desired relations for y_A, y_B, and V, respectively, when $V_0 > 0$ and $V < 0$.

For $V_0 < 0$, $V > 0$, the wave heights and velocities in the region of the friction barrier just before the arrival of the incoming waves are shown in Figure 5. The diagram of the conditions existing in the friction barrier region immediately following the arrival and reflection of the incoming waves consistent with the velocities noted above is given in Figure 6.

The height y_A of the water surface on the A side of the friction barrier after the reflection of the incoming waves is

$$y_A = y_0 + 2y_1 - (a/g)\,(V - V_0) \qquad V_0 < 0,\ V > 0 \quad \ldots\ldots\ldots\ldots (14)$$

In like manner, the height y_B of the water surface on the B side of the barrier after the reflection of the waves is

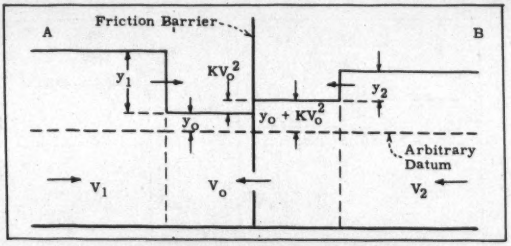


Fig. 5--Conditions at friction barrier just before arrival of waves for $V_0 < 0$, $V > 0$

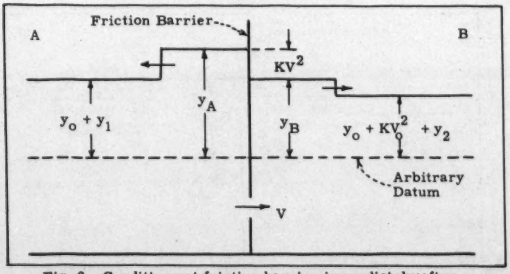


Fig. 6--Conditions at friction barrier immediately after arrival and reflection of waves for $V_0 < 0$, $V > 0$

$$y_B = y_0 + KV_0^2 + 2y_2 + (a/g)(V - V_0) \qquad V_0 < 0, V > 0 \quad \ldots\ldots\ldots (15)$$

From inspection of Figure 6, it is seen that

$$y_A = y_B + KV^2 \quad \ldots\ldots\ldots (16)$$

After substituting (14) and (15) into (16), we obtain the following relation:

$$V^2 + (2a/gK)V - (2/K)(y_1 - y_2) - (2a/gK)V_0 + V_0^2 = 0 \quad \ldots\ldots\ldots (17)$$

Solving for V, we obtain

$$V = -a/gK \pm \sqrt{a^2/g^2K^2 + (2/K)(y_1 - y_2) + (2a/gK)V_0 - V_0^2} \quad \ldots\ldots\ldots (18)$$

The initial and boundary conditions require that V_0 be a negative quantity while V must be a positive quantity. Consistent with the requirements, we obtain

$$V = -a/gK \pm \sqrt{a^2/g^2K^2 + (2/K)(y_1 - y_2) + (2a/gK)V_0 - V_0^2} \qquad V_0 < 0, V > 0 \ldots (19)$$

Equations (14), (15), and (19) are, then, the desired relations for y_A, y_B, and V, respectively, when $V_0 < 0$ and $V > 0$.

For $V_0 < 0$, $V < 0$, the wave heights and velocities in the region of the friction barrier just before the arrival of the incoming waves are as shown in Figure 7. The diagram of the conditions existing in the friction barrier region immediately following the arrival and reflection of the incoming waves consistent with the velocities noted above is given in Figure 8.

The height y_A of the water surface on the A side of the friction barrier after the reflection of the incoming waves is

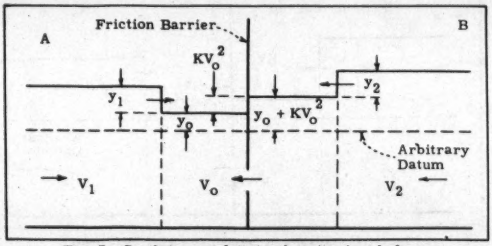


Fig. 7--Conditions at friction barrier just before arrival of waves for $V_0 < 0$, $V < 0$

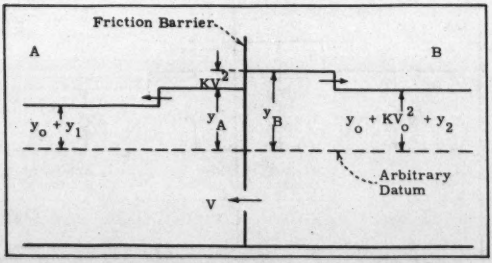


Fig. 8--Conditions at friction barrier immediately after arrival and reflection of waves for $V_0 < 0$, $V < 0$

$$y_A = y_0 + 2y_1 - (a/g)(V - V_0) \qquad V_0 < 0, V < 0 \quad \ldots\ldots\ldots\ldots (20)$$

In like manner, the height y_B of the water surface on the B side of the barrier after the reflection of the waves is

$$y_B = y_0 + KV_0^2 + 2y_2 + (a/g)(V - V_0) \qquad V_0 < 0, V < 0 \quad \ldots\ldots\ldots (21)$$

From inspection of Figure 8, it is seen that

$$y_B = y_A + KV^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (22)$$

After substituting (20) and (21) into (22), we obtain

$$V^2 - (2a/gK)V + (2/K)(y_1 - y_2) + (2a/gK)V_0 - V_0^2 = 0 \quad \ldots\ldots\ldots\ldots (23)$$

Solving for V, we obtain

$$V = a/gK \pm \sqrt{a^2/g^2K^2 - (2/K)(y_1 - y_2) - (2a/gK)V_0 + V_0^2} \quad \ldots\ldots\ldots (24)$$

The initial and boundary conditions require that both V_0 and V be negative quantities. Consistent with the requirements, we obtain

$$V = a/gK - \sqrt{a^2/g^2K^2 - (2/K)(y_1 - y_2) - (2a/gK)V_0 + V_0^2} \qquad V_0 < 0, V < 0 \qquad (25)$$

Equations (20), (21), and (25) are, then, the desired relations for y_A, y_B, and V, respectively, when $V_0 < 0$ and $V < 0$.

Formulas for division of waves at a three-way stream junction

Incoming wave in channel I--In order to determine the flows in an interconnected system of estuarine channels produced by tidal variations using the method proposed herein, it is necessary to determine how a bore or surge wave divides upon reaching a junction of three streams. The method employed is similar to that used for the division of water hammer pressure waves in pipes and penstocks [BUREAU OF RECLAMATION, 1940, pp. 119-122].

Consider the junction of the three streams shown in Figure 9. A wave of height h_1 is considered to be approaching the junction with a celerity [ROUSE, 1946, pp. 143-145] a_1 leaving behind it a velocity V_1 of the water in channel I whose area is A_1 and mean depth d_{m_1}. Before proceeding with the derivation of the desired relations, it is well to introduce certain definitions similar to those used in water hammer analyses [BUREAU OF RECLAMATION, 1940, pp. 119-122]. The increment of velocity associated with a surge wave is defined as the velocity behind the wave

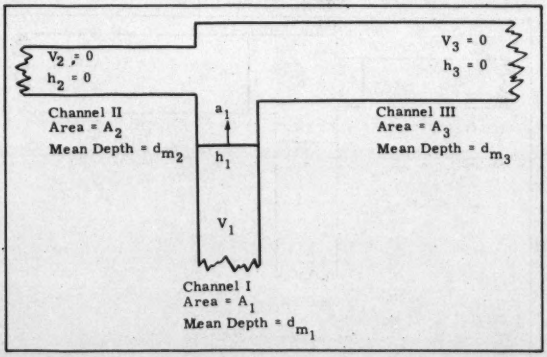


Fig. 9--Conditions at junction just before arrival of incoming wave

minus the velocity ahead of the wave. Similarly, the height of a wave may be defined as the height of the water surface behind the wave minus the height of the water surface ahead of the wave.

It is tacitly assumed in the present study that the celerity of a bore or surge wave is large compared to the average velocity of the water flowing in the channel. The velocities V_2 and V_3 in channels II and III, respectively, are taken as being equal to zero. This procedure is followed merely for convenience. Initial values for these velocities could have been assumed without affecting the results of the study since we are concerned only with a change in velocity produced by a surge or bore wave of a given magnitude. The heights h_2 and h_3 are taken as being equal to zero initially since it is assumed that no waves are approaching the junction in channels II and III initially.

When the incoming wave of height h_1 reaches the junction of the three streams, it will be reduced in height because of the increased surface area presented to the wave by the two channels. Waves of this reduced height will then travel down the two channels away from the junction with celerities dependent upon the mean depths of the channels. A negative wave travels back along the channel of the initial wave.

It is desired to determine the height h of the waves which travel along channels II and III which were produced by the incoming wave in channel I. The conditions existing in the channels immediately after the arrival of the incoming wave are shown in Figure 10.

If we consider channel III, we may write the following relation based upon an application of (1) of this discussion.

$$(h - 0) = (a_3/g)(V_3 - 0) \quad \text{or} \quad h = \lambda_3 V_3 \ldots\ldots\ldots\ldots \quad (26)$$

Similarly, expressions may be written which relate the wave heights and velocities in channels I and II.

$$(h - 0) = (a_2/g)(V_2 - 0) \quad \text{or} \quad h = \lambda_2 V_2 \ldots\ldots\ldots\ldots\ldots\ldots \quad (27)$$

and

$$(h - h_1) = -\lambda_1 (V_4 - V_1) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (28)$$

The continuity of flow condition requires the quantity of water flowing into the junction be equal to that flowing out of the junction.

Expressed mathematically this relation is

$$A_2 V_2 + A_3 V_3 = A_1 V_4 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (29)$$

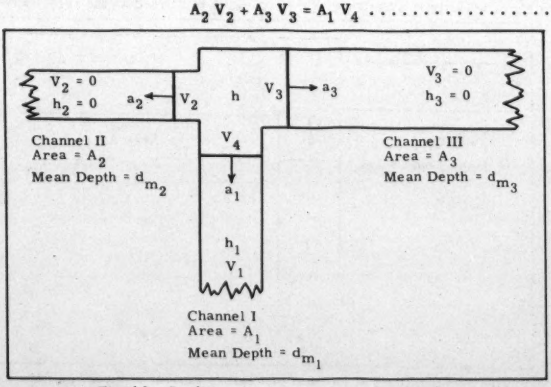


Fig. 10--Conditions at junction immediately after arrival of incoming wave

From (26), (27), (28), and (29) we obtain

$$h = 2\lambda_2\lambda_3 A_1 h_1/(\lambda_2\lambda_3 A_1 + \lambda_1\lambda_3 A_2 + \lambda_1\lambda_2 A_3) \quad \ldots\ldots\ldots\ldots (30)$$

Incoming wave in channel II--If the incoming wave of height h_1 approaches the junction along channel II, the following expression gives the relation for the wave height h:

$$h = 2\lambda_1\lambda_3 A_2 h_1/(\lambda_2\lambda_3 A_1 + \lambda_1\lambda_3 A_2 + \lambda_1\lambda_2 A_3) \quad \ldots\ldots\ldots\ldots (31)$$

Incoming wave in channel III--Similarly, if the incoming wave of height h_1 approaches the junction along channel III, the following expression gives the relation for the wave height h:

$$h = 2\lambda_1\lambda_2 A_3 h_1/(\lambda_2\lambda_3 A_1 + \lambda_1\lambda_3 A_2 + \lambda_1\lambda_2 A_3) \quad \ldots\ldots\ldots\ldots (32)$$

Approximation of tidal fluctuations

The computation of flows in a particular system of estuarine channels, which are due to the combined action of gravity and tidal flows, requires the knowledge and use of the tidal fluctuations for the given channels. As noted [PILLSBURY, 1940, pp. 1-75, 227-249], the tides vary in character and magnitude throughout the world, and are of three general types. A tide type is determined by the relative magnitudes of the principal semidiurnal components and the principal diurnal components of the tide. The magnitudes of the principal components vary from place to place throughout the world giving rise to the semidiurnal, diurnal, and mixed types of tides.

As stated by Pillsbury, the tidal variation at any point may be assumed to be the resultant of a limited number of sinusoidal curves whose periods are determined by the periods of the tide-producing forces. At most locations the lunar components will make up the greater part of the resultant tide with the principal lunar component being the largest of the group. The principal solar component is usually the largest of the remaining components.

The amplitude and initial phase angle of each tidal component at a given location may be computed from a record of the hourly tidal heights of sufficient length by the process of harmonic analysis. The hourly heights may be obtained by observation or from a continuous automatic tidal height recorder. The method of harmonic analysis is discussed in detail by PILLSBURY [1940, Chap. 2]. The minimum length of tide record necessary to determine a particular component is also discussed by Pillsbury.

The procedure which has been followed here is to determine the largest lunar components of the tides from the recorded tidal heights and to use these components in the computations to determine the channel flows. The solar components, generally, will add little, if any, flow to that computed using the lunar tidal components since the solar components reinforce the lunar a portion of the time and reduce them the remaining time. Refinements which take into account the effects produced by various other components can be made but are not always necessary or justified.

The principal lunar components of the tides at various stations throughout the estuarine channel system are determined from the harmonic analyses to be sinusoidal functions of height versus time with a particular phase angle for each location. Since the present method of analysis is essentially numerical as differentiated from strictly analytical, the sinusoidal tidal variations used in the study must be approximated by step-wise functions consisting of a number of small waves originating at equal intervals of time. The changes in height of the water surface at the specified stations throughout the system due to tidal fluctuations are thus assumed to take place as sharp impulses instead of being distributed over the increment of time. Since the differential equations in the theory underlying the action of bore or surge waves are linear, the sum of any number of solutions of the type used herein will also be a solution. The law of superposition is, therefore, valid and applicable to the present study. The computational method is essentially a process of summation in which the wave heights and velocity increments due to the elementary wave components are accounted for as they propagate back and forth throughout the channel system.

Some comments on the magnitude of the time increment between successive changes in water surface height are pertinent. As the increment is made smaller and smaller, the accuracy of the computations becomes greater and greater, tending to approach that of an analytical solution. As the length of the time interval is decreased, however, the amount of computation which must be done increases. It is necessary, therefore, to exercise judgment in choosing the length of the time interval between successive waves in order to provide sufficient accuracy and prevent excessive labor of calculation. The length of the time increment is also so chosen so that an integral number

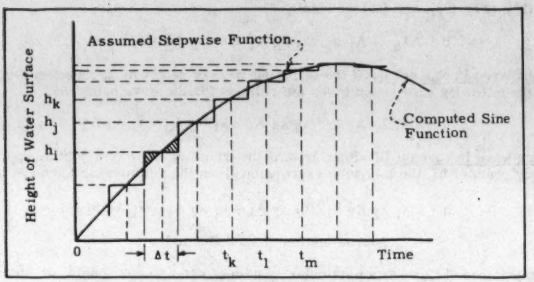


Fig. 11--Curves of computed and assumed values of water surface heights

of increments are contained in the times required for a wave to travel the lengths of the various individual channels in the system. Often it is convenient to modify the channel lengths slightly so as to have waves arriving and reflecting or combining at the proper times at certain points in the system.

Much of the error caused by assuming the water-surface height to remain constant during a time interval can be reduced by using the value of the water-surface height at the middle of the interval instead of that of the beginning. By referring to Figure 11, it is noted that the water-surface height at the middle of the time interval is approximately equal to the average height during the interval. This is shown by the fact that the areas of the shaded triangles above and below the true curve for a given time interval are approximately equal.

Problem procedure

The following procedure is suggested for a given problem wherein it is desired to determine, for a system of interconnected channels, the flows produced by normal gravity action and tidal fluctuations throughout the system. The method of analysis may be used to determine flows in a channel system as it exists naturally; in a system modified by man so as to include new channels or to eliminate previously existing ones; or in a natural system modified to include mechanical equipment to control flows, such as tidal gates and control weirs.

Determine natural gravity flows--The first step in the suggested procedure is to determine the flows which would exist in the system caused by the action of gravity only. Such an analysis may be made using a method such as that of CROSS [1936], and requires a knowledge of the section properties of the various channels throughout the system. These properties include the widths, depths, frictional coefficients, incoming flows into the system, and other factors which may be pertinent to the particular problem. If new channels are proposed for the system, their characteristics should be estimated to the best possible degree of accuracy using data from existing channels in the same area. The flows determined from this gravity analysis represent initial conditions for the combined flow problem.

Determine principal tide components--The second step in the procedure is to determine the principal solar and lunar components of the resultant tide at as many stations throughout the system as may be deemed desirable, or at as many stations as possible if complete data at all desired locations are not available. The records should be of sufficient duration and accuracy to guarantee the determination of a desired component and the elimination of all others in a particular analysis. As noted by PILLSBURY [1940, p. 48], "a period of 29 days affords fair determinations if corrections are applied to eliminate the residual effect of interfering components."

It is usually desirable to determine both the principal lunar and principal solar components of the tides so that their magnitudes can be compared one with the other and also with the magnitude of the actual resultant tide. The sinusoidal principal lunar components, including magnitudes and relative phase angles, determined from the analyses for the desired stations in the channel system are then used in the combined flow study.

Determine friction barrier relations--From the equations derived above, and the physical characteristics of the various channels, the relations for the velocities and wave heights existing at the barrier before and after the arrival of the incoming surge waves due to the tidal fluctuations may be determined. Tabulating sheets are prepared for the barrier computations since, for a complete tidal cycle study, calculations must be made for each time increment in the cycle. Sample calculations are presented in the illustrative example.

Determine channel junction relations--From the equations derived above for junctions, and the physical dimensions of the various channels, the relations for the division of waves at a three-way stream junction may be determined. Tabulating sheets are also prepared for each junction so that the series of computations for each junction for a complete tidal cycle may be tabulated in order.

Determine channel flows during tidal cycle--Using the relations and computation forms prepared according to the two immediately preceding paragraphs above together with the magnitudes of the tidal heights as determined in paragraph above on tide components, the wave heights, velocities, and flows at the desired points or stations in the channel system are computed. These calculations are begun using the gravity flows as the initial flows. The water surface heights as required by the tidal variations are then imposed upon the system. This procedure usually requires a large initial wave on one or more of the channels with the result that it is usually necessary to make the computations for a total period somewhat greater than one complete tidal cycle. The computations should be continued into the second cycle of tidal fluctuations until values of channel velocity, flow, and wave heights begin to duplicate values obtained in the first tidal cycle.

Illustrative example

As a means of demonstrating the application of the foregoing principles and relations, the following illustrative example is presented. The problem deals generally with the estuarine area

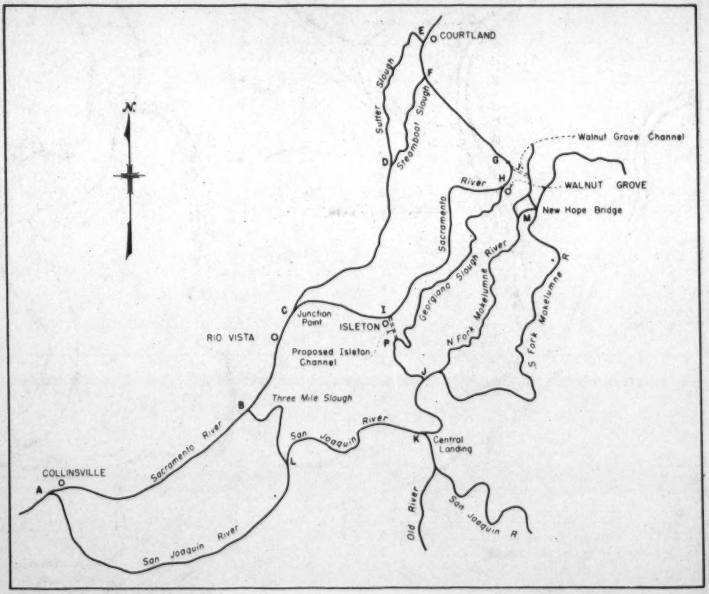


Fig. 12--Principal interconnected channels in Sacramento - San Joaquin delta area, California

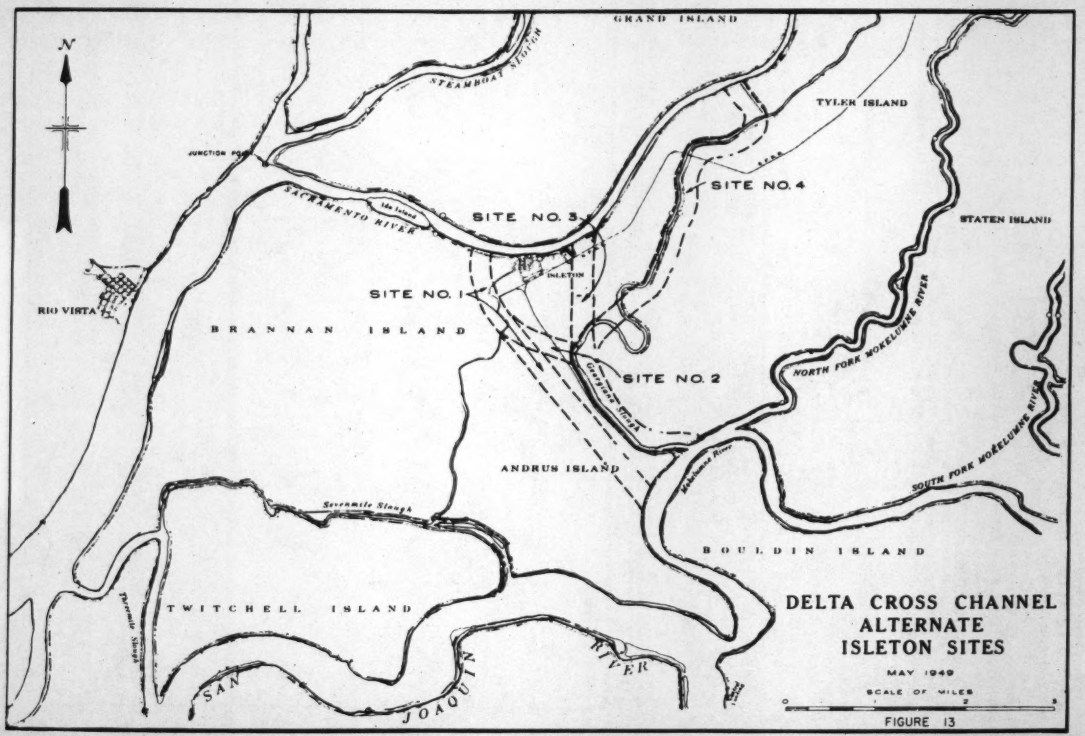

N
GRAND ISLAND
STEAMBOAT SLOUGH
TYLER ISLAND
JUNCTION POINT
SITE NO. 4
SITE NO. 3
SACRAMENTO RIVER
STATEN ISLAND
ISLETON
RIO VISTA
SITE NO. 1
BRANNAN ISLAND
NORTH FORK MOKELUMNE RIVER
SITE NO. 2
GEORGIANA SLOUGH
ANDRUS ISLAND
Mokelumne River
SOUTH FORK MOKELUMNE RIVER
Sevenmile Slough
BOULDIN ISLAND
TWITCHELL ISLAND
Threemile Slough
SAN JOAQUIN RIVER
DELTA CROSS CHANNEL
ALTERNATE
ISLETON SITES
MAY 1949
SCALE OF MILES
0 1 2 3

FIGURE 13

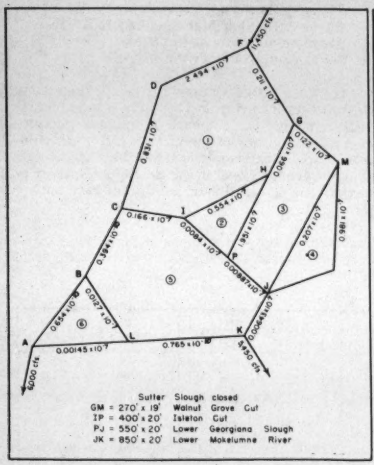


Fig. 14--Delta cross-channel problem; simplified flow chart showing flows into and out of system, and channel friction factors

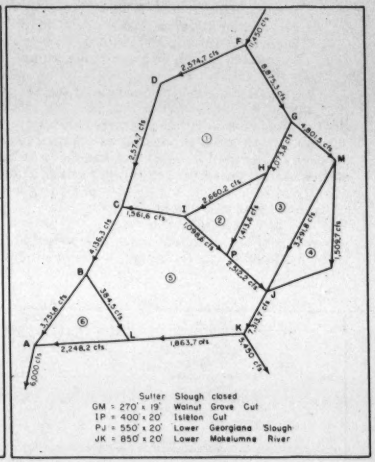


Fig. 15--Delta cross-channel problem; simplified flow chart showing final distribution of gravity flows

of the delta region of the Sacramento and San Joaquin Rivers in central California, and involves specifically a study of the possible increased flow from the Sacramento River to the San Joaquin River because of the presence of additional man-made channels between the two streams. Figure 12 is a sketch showing the principal interconnected channels forming the delta area together with the locations of the proposed cross channels. All of the streams shown are subject to tidal fluctuations of varying magnitudes and time phases. (The channel at Walnut Grove is currently under construction.)

The proposed channel between the two rivers in the vicinity of Isleton is so located as to attempt to utilize the differences in tidal heights and phases which exist between the streams at this site. By the use of tidal gates at one end of this proposed channel, flow through it could be restricted to that which would be favorable to the desired transfer of water. Figure 13 is a map of the delta area in the vicinity of Isleton showing the alternate sites for the proposed cross channel at that location.

Natural distribution of flows--The first step in the problem is to determine the natural distribution of flows in the various channels caused by gravity only. A simplified diagram of the interconnected channels together with the inflow to and the outflow from the system is given in Figure 14. The numerical values shown for each channel are friction factors which when multiplied by the square of the flow Q in that channel gives the friction head loss for the entire length of channel. These factors are determined by calculation knowing the channel characteristics or by field measurements.

The final distribution of flows in the interconnected system because of gravity alone is given on Figure 15. The flows were determined by the Hardy Cross method.

Principal tide components--The second step in the problem is to determine from records of tidal variations the principal solar and lunar components of the tides at as many stations as desired in the channel system. In the present study continuous tidal records were available for the period July 1, 1949, to August 13, 1949, for the following stations in the delta area:

Sacramento River at Walnut Grove
Mokelumne River at New Hope Bridge
Sacramento River at Isleton
Georgiana Slough at Mokelumne River
Three-Mile Slough at Sacramento River
Three-Mile Slough at San Joaquin River
Sacramento River at Rio Vista
Sacramento River at Collinsville

Harmonic analyses were made of the records from the above stations for two periods; namely, from July 1 through July 30, 1949, and from July 16 through August 13, 1949. The principal tidal components were thus determined for two different time periods each of one lunar month duration which made it possible to obtain a check on the accuracy of the method and of the computations. Figure 16 presents a summary of the principal lunar components of the tides at the stations noted above for the two periods of time. The average flows in the Sacramento River at the city of Sacramento for the two periods are also given. The Pillsbury method of harmonic analysis was used in the study.

A plot of the principal lunar components of the tides at the two stations at the ends of the proposed Isleton cross channel, as determined from the harmonic analysis, is given in Figure 17.

LOCATION	A PRINCIPAL LUNAR COMPONENT 7-1-49 THROUGH 7-30-49	B PRINCIPAL LUNAR COMPONENT 7-16-49 THROUGH 8-13-49	AVERAGE OF LUNAR COMPONENTS "A" & "B"
Sacramento R. @ Walnut Grove	$y = 0.93\cos(m_2t - 280°12')$	$y = 0.91\cos(m_2t - 282°03')$	$y = 0.92\cos(m_2t - 281°08')$
Mokelumne R. @ New Hope Bridge	$y = 1.005\cos(m_2t - 324°27')$	$y = 1.007\cos(m_2t - 324°16')$	$y = 1.006\cos(m_2t - 324°22')$
Sacramento R. @ Isleton	$y = 1.28\cos(m_2t - 246°53')$	$y = 1.28\cos(m_2t - 246°36')$	$y = 1.28\cos(m_2t - 247°44')$
Georgiana Slough @ Mokelumne R.	$y = 0.970\cos(m_2t - 297°37')$	$y = 0.973\cos(m_2t - 298°14')$	$y = 0.97\cos(m_2t - 297°56')$
Three-Mile Slough @ Sacramento R.	$y = 1.33\cos(m_2t - 245°30')$	$y = 1.33\cos(m_2t - 244°15')$	$y = 1.33\cos(m_2t - 244°52')$
Three-Mile Slough @ San Joaquin R.	$y = 0.918\cos(m_2t - 264°40')$	$y = 0.924\cos(m_2t - 262°56')$	$y = 0.92\cos(m_2t - 263°48')$
Sacramento R. @ Rio Vista	$y = 1.434\cos(m_2t - 240°11')$	$y = 1.433\cos(m_2t - 238°55')$	$y = 1.43\cos(m_2t - 239°33')$
Sacramento R. @ Collinsville	$y = 1.298\cos(m_2t - 218°30')$	$y = 1.279\cos(m_2t - 224°16')$	$y = 1.29\cos(m_2t - 221°23')$
	Average discharge of Sacramento River at Sacramento = 7,048 cfs.	Average discharge of Sacramento River at Sacramento = 6,925 cfs.	Note: Tide height expressed in feet.

Fig. 16--Delta cross-channel; summary of analyses of tide records, principal lunar components

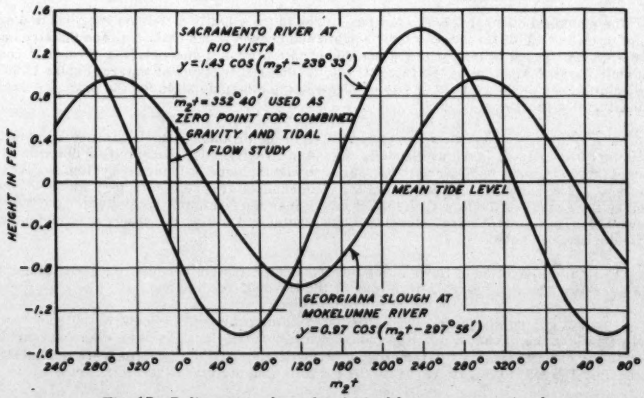


Fig. 17--Delta cross-channel; principal lunar components of tides at ends of Isleton channel

The graph shows the differences in magnitudes and time phases between the two components which are useful in causing an additional flow of water from the Sacramento River to the San Joaquin River if tidal gates are used in the channel. The figure also shows the time chosen as the zero or initial point for the combined gravity and tidal flow computation. In the numerical computation, points are computed on each curve for each time increment by the use of ordinary trigonometric tables.

Friction barrier relations--Since, in this study, only the Isleton channel of the added channels is to be studied in connection with increased transfer flow due to tidal action, it is not necessary to include all of the delta streams shown on Figure 12 in the analysis. Only those channels in the vicinity of the Isleton cross channel will be considered in the further steps of the investigation. Figure 18 is a sketch of the channels taken in the study showing the designations and assumed locations of the friction barriers, the designation of the channel junctions, and some of the associated data for the various channels. The values of Q_0 shown are the initial flows as determined by the gravity analysis.

From the equations developed above, and the constants noted on Figure 18, the relations for velocities and wave heights at each of the friction barriers may be determined. A summary of these relations is given on Figure 19.

Channel junction relations--From the relations given earlier for junctions, and the constants noted on Figure 18, the relations for the wave heights at stream junctions I, P, and J may be obtained. A summary of these relations is given on Figure 20.

Numerical computations--After determining the friction-barrier and channel-junction relations and before starting the numerical computations, it is necessary to give consideration to the times required for the surge waves to travel the lengths of the various channels. In order to simplify and expedite the computations, it is desirable to have coincident arrival of waves at a barrier or junction at a given instant of time. Consistent with the required problem accuracy, a time increment is chosen for the computations which is small enough to permit expressing, to a satisfactory degree of approximation, the length of each component channel of the system in terms of the product of the celerity of the wave and an integral number of time increments. This procedure

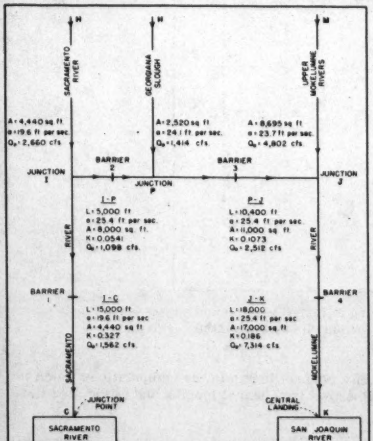


Fig. 18--Sketch of channels and associated data for Isleton cross-channel study

BARRIER 1:

$$V = \pm 1.8615 + \sqrt{3.4652 + 6.1162(y_i - y_t) + 3.723V_0 \pm V_0^2}$$

$$y_t = y_0 + 2y_i - 0.6087(V - V_0)$$

$$y_i = y_0 + 0.327V_0^2 + 2y_t + 0.6087(V - V_0)$$

BARRIER 2:

$$V = \pm 14.581 + \sqrt{212.60 + 36.969(y_i - y_t) + 29.162V_0 \pm V_0^2}$$

$$y_t = y_0 + 2y_i - 0.7888(V - V_0)$$

$$y_i = y_0 + 0.0541V_0^2 + 2y_t + 0.7888(V - V_0)$$

BARRIER 3:

$$V = \pm 7.3515 + \sqrt{54.045 + 18.639(y_i - y_t) + 14.703V_0 \pm V_0^2}$$

$$y_t = y_0 + 2y_i - 0.7888(V - V_0)$$

$$y_i = y_0 + 0.1073V_0^2 + 2y_t + 0.7888(V - V_0)$$

BARRIER 4:

$$V = \pm 4.2410 + \sqrt{17.986 + 10.753(y_i - y_t) + 8.482V_0 \pm V_0^2}$$

$$y_t = y_0 + 2y_i - 0.7888(V - V_0)$$

$$y_i = y_0 + 0.186V_0^2 + 2y_t + 0.7888(V - V_0)$$

NOTES:
Sign of V_0^2 is positive in expression for V if ($V_0 > 0$, $V = 0$) or ($V_0 = 0$, $V < 0$), negative if ($V_0 = 0$, $V = 0$) or ($V_0 < 0$, $V > 0$).
Sign of V_0^2 is positive in y_G, y_I, y_J, and y_K if $V_0 = 0$, negative if $V_0 = 0$.
Sign of $(y_i - y_t)$ term and radical are positive if $V = 0$, negative if $V = 0$.
Sign of first term in expression for V is opposite to that of radical.

Fig. 19--Summary of friction barrier relations; Isleton cross channel

JUNCTION	CHANNEL IN WHICH WAVE APPROACHES JUNCTION	HEIGHT h OF WAVE AFTER ARRIVAL AT JUNCTION
I	I1	$h = 0.58990h_{I1}$
	I2	$h = 0.82020h_{I2}$
	IH	$h = 0.58990h_{IH}$
P	P2	$h = 0.73883h_{P2}$
	P3	$h = 1.0159\ h_{P3}$
	PH	$h = 0.24527h_{PH}$
J	J3	$h = 0.58952\ h_{J3}$
	J4	$h = 0.91107\ h_{J4}$
	JM	$h = 0.49941\ h_{JM}$

Fig. 20--Wave height relations at stream junctions; Isleton cross channel

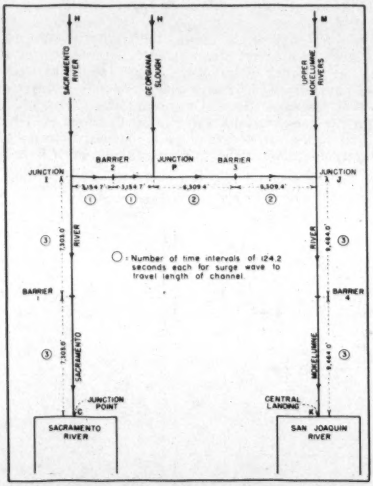


Fig. 21--Sketch showing adjusted lengths and time intervals for various channels; Isleton cross-channel study

often necessitates, as suggested above, the use of a channel length in the computations which is slightly different than the true length. Figure 21 shows the channel lengths and associated time increments used in the Isleton channel study.

Since the period of the mean lunar day is approximately 24.8412 mean solar hours, the period for one complete cycle of the principal lunar component of the tide is 12.4206 mean solar hours. One degree on the tidal cycle, therefore, corresponds to 0.03450 hours or 124.20 seconds. A time increment of 124.20 seconds was chosen as the basic interval for the computation since it takes approximately this length of time for surge waves to travel the Isleton channel from Junction I or P to Barrier 2.

Table 1--Tabulation of computations for points C and K, Isleton cross channel

	POINT C				POINT K			
A	B	C	D	E	F	G	H	I
TIME INTERVAL	SACRAMENTO RIVER LEVEL	HEIGHT OF WAVE RETURNING FROM BARRIER 1	SUM OF RIVER LEVEL AT PREVIOUS TIME INCREMENT AND HEIGHT OF RETURNING WAVE	HEIGHT OF INCREMENT TO BARRIER 1 (B-D)	SAN JOAQUIN RIVER LEVEL	HEIGHT OF WAVE RETURNING FROM BARRIER 4	SUM OF RIVER LEVEL AT PREVIOUS TIME INCREMENT AND HEIGHT OF RETURNING WAVE	HEIGHT OF INCREMENT TO BARRIER 4 (F-H)
	(ft)	(ft)	(ft)	(ft)	(ft)	(ft)	(ft)	(ft)
0	-0.5614	0.0006	0.0006	-0.5620	0.5601	0.0000	0.0000	0.5601
1	-0.5843	0.0000	-0.5614	-0.0229	0.5462	0.0000	0.5601	-0.0139
2	-0.6070	0.0000	-0.5843	-0.0227	0.5321	0.0000	0.5462	-0.0141
3	-0.6295	0.0000	-0.6070	-0.0225	0.5178	0.0000	0.5321	-0.0143
4	-0.6518	0.0000	-0.6295	-0.0223	0.5035	0.0000	0.5178	-0.0143
5	-0.6739	0.0000	-0.6518	-0.0221	0.4889	0.0000	0.5035	-0.0146
6	-0.6958	-0.1517	-0.8256	0.1298	0.4742	0.0230	0.5119	-0.0377
7	-0.7175	-0.0082	-0.7040	-0.0135	0.4594	-0.0008	0.4734	-0.0140
8	-0.7390	-0.0083	-0.7258	-0.0132	0.4444	-0.0006	0.4588	-0.0144
9	-0.7603	-0.0083	-0.7473	-0.0130	0.4293	-0.0007	0.4437	-0.0144
10	-0.7813	-0.0084	-0.7687	-0.0126	0.4140	-0.0006	0.4287	-0.0147
11	-0.8021	-0.0084	-0.7897	-0.0124	0.3987	-0.0005	0.4135	-0.0148
12	-0.8226	0.1534	-0.6487	-0.1739	0.3832	-0.0474	0.3513	0.0319

Table 2--Tabulation of computations for barriers 1 and 4, Isleton cross channel

TIME INTERVAL	BARRIER 1			BARRIER 4		
	y_t	y_c	v	y_s	y_k	v
0			0.3514			0.4303
	0.0410	0.0006		0.0344	0.0000	
1			0.3514			0.4303
	0.0410	0.0006		0.0344	0.0000	
2			0.3514			0.4303
	0.0410	0.0006		0.0344	0.0000	
	0.0000	-0.5620		0.0000	0.5601	
	0.0410	-0.5614		0.0344	0.5601	
3	-0.4103	-0.1517	1.0254	0.5370	0.0230	-0.2505
	-0.3693	-0.7131		0.5714	0.5831	
	0.0000	-0.0229		0.0000	-0.0139	
	-0.3693	-0.7360		0.5714	0.5692	
4	-0.0147	-0.0082	1.0496	-0.0131	-0.0008	-0.2339
	-0.3840	-0.7442		0.5583	0.5684	

It is convenient to tabulate the results of the computations on forms such as those used for Tables 1 through 5 which follow. Table 1 is a tabulation of the water surface heights at points C and K as determined from the tide records, the magnitudes of the waves returning from barriers 1 and 4, and the height of the wave increments which are sent to barriers 1 and 4 from points C and K. The tidal variations used at points C and K were those determined from the tide records at Rio Vista and at the junction of the Mokelumne River and Georgiana Slough. No records were taken at Junction Point or Central Landing; consequently, it was necessary to use the records nearest these locations. It was assumed in the study that the presence of the Isleton cross channel would not alter the tidal variations in the large channels of the Sacramento and San Joaquin Rivers below Junction Point and Central Landing, respectively.

Table 3--Tabulation of computations for barriers 2 and 3, Isleton cross channel

TIME INTERVAL	BARRIER 2			BARRIER 3		
	y_1	y_p	v	y_p	y_2	v
0			0.1375			0.2286
	0.0410	0.0400		0.0400	0.0344	
1			0.1375			0.2286
	0.0410	0.0400		0.0400	0.0344	
2			0.1375			0.2286
	0.0410	0.0400		0.0400	0.0344	
	Above values duplicated through Time Interval 6					
	-0.2420	0.0000				
	-0.2010	0.0400				
7	-0.0013	-0.2408	-0.1677			0.2286
	-0.2023	-0.2008		0.0400	0.0344	
	-0.0087	0.0000		0.0000	0.4892	
	-0.2110	-0.2008		0.0400	0.5236	
8	-0.0001	-0.0086	-0.1786	0.4787	0.0105	-0.3783
	-0.2111	-0.2094		0.5187	0.5341	

Table 4--Tabulation of computations for junctions I and J, Isleton cross channel

TIME INTERVAL	JUNCTION I			JUNCTION J		
	y_1	y_2	y_H	y_4	y_3	y_M
0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	Above values duplicated through Time Interval 5					
	-0.4103	0.0000		0.5370	0.0000	
6	-0.1683	-0.2420		-0.0478	0.4892	
	-0.2420	-0.2420	-0.2420	0.4892	0.4892	0.4892
	-0.0147	0.0000		-0.0131	0.0000	
7	0.0060	-0.0087		0.0012	-0.0119	
	-0.0087	-0.0087	-0.0087	-0.0119	-0.0119	-0.0119

Table 2 is a tabulation of the computations for barriers 1 and 4 while Table 3 is a tabulation of similar calculations for barriers 2 and 3. For each barrier, computations are made to determine wave heights on each side of the barrier as well as the velocity of the water through it. The following entries are made for each time interval:

Second line above time entry contains wave height increments coming to the barrier from the respective junctions or tidal basins.

First line above time entry contains entries representing conditions just before the reflection and division of waves at the barrier. Each entry is the sum of the previous water surface height on a given side of the barrier plus the height of the incoming wave.

Table 5--Tabulation of computations for junction P, Isleton cross channel

TIME INTERVAL	JUNCTION P		
	y_2	y_3	y_4
0	0.0000	0.0000	0.0000
1	0.0000	0.0000	0.0000
2	0.0000	0.0000	0.0000
	Above values duplicated through Time Interval 7		
	-0.2408	0.0000	
8	0.0629	-0.1779	
	-0.1779	-0.1779	-0.1779
	-0.0086	0.0000	
9	0.0022	-0.0064	
	-0.0064	-0.0064	-0.0064

Line opposite time entry contains the outgoing wave height increments from the barrier and the new velocity through the barrier. The outgoing wave-height increments are equal to the values given in the line below the time entry minus the values given in the first line above the time entry. The values given on the line opposite the time entry are computed after those on the line below the time entry are determined.

Line below time entry contains the values of the water surface heights behind the outgoing waves. These values are computed from the relations given for the various y's on Figure 19.

Table 4 is a tabulation of computations for junctions I and J, while Table 5 is a tabulation of similar calculations for junction P. These computations give the wave heights resulting at the junctions due to the waves coming into the junction along the various channels. The following entries are made for each time interval:

Line above time entry contains the heights of the incoming waves to the junction.

Line opposite time entry contains the heights of the outgoing waves from the junction. These values are equal to the values given on the line below the time entry minus those on the line above the time entry. The values on the line opposite the time entry are computed after those on the line below the time entry are determined.

Line below time entry contains the value of the water surface height at the junction behind the outgoing wave. These values are computed from the relations for the various h's given on Figure 20.

In this study it has been assumed that the Sacramento River above junction I, the Georgiana Slough above junction P, and the upper Mokelumne Rivers above junction J are all streams of such length that no reflections occur in them with the result that no waves enter the junctions from these channels.

Results of study--The principal results of the study are shown on Figure 22 which gives the flows through barriers 1 through 4 caused by the combined tidal and gravity flows over a complete tidal cycle. The flows as given do not include the effects of any tidal gates on any of the channels. The net flows with such structures present may be readily determined, however, by considering that they prevent any flow in a given channel when it is not in the desired direction.

Examination of Figure 22 reveals that for the early time increments, the flows are erratic and do not conform to a cyclic pattern. This is because of the shock imposed upon the system by the large increments of tidal variation which were introduced at time $t = 0$. Once the effects of this sudden change have been damped out, the system settles down and becomes periodic in nature. It will be noted that approximately 50 time intervals are required to smooth out the initial fluctuations. One complete tidal cycle plus approximately 50 time intervals are necessary, then, before

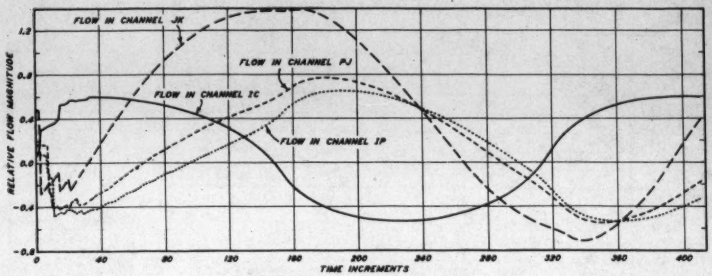


Fig. 22--Summary graph; time variation of relative flow magnitudes in principal channels; Isleton cross-channel study

the channel flows begin to repeat themselves with the accuracy which should be associated with the study. A study of the graph will show that the four flows represented have begun to repeat themselves very closely. Confirmation of the validity of the method and the accuracy of the computations is thus obtained.

A check of the method and results has been made using a graphical procedure similar to the technique used in solving water hammer problems by graphical means. The method was devised by John Parmakian of the Bureau of Reclamation, Denver, Colorado. The procedure is both rapid and accurate, and can be carried through by inexperienced personnel after a brief period of instruction. The analytical method of solution has also been checked using electric analog computers.

Acknowledgments

Many persons have assisted in the development of the method of analysis presented herein. F. W. Taylor checked the derivations of the formulas and performed many of the check computations for the illustrative problem. K. L. Shine made the computations for the illustrative example, the principal results of which are summarized on Figure 22. R. H. Williams was responsible for the figures and charts.

The material contained in this paper has been extracted from Technical Memorandum No. 640 of the Branch of Design and Construction, Bureau of Reclamation, Denver, Colorado.

References

BUREAU OF RECLAMATION, Penstock analysis and stiffener design, Bull. 5, pt. V, Boulder Canyon Project Final Reports, Supt. of Documents, U. S. Government Printing Office, Washington, D. C., 1940.

CROSS, HARDY, Analysis of flow in networks of conduits or conductors, Bull. 286, Eng. Exp. Sta., University of Illinois, 1936.

JOHNSON, R. D., Surges in an open canal, Trans. Amer. Soc. Civil Eng., v. 81, pp. 112-115, 1917.

PILLSBURY, GEORGE B., Tidal hydraulics, Supt. of Documents, U. S. Government Printing Office, Washington, D. C., 1940.

ROUSE, HUNTER, Fluid mechanics for hydraulic engineers, McGraw-Hill Book Co., 1938.

ROUSE, HUNTER, Elementary mechanics of fluids, John Wiley, 1946.

WOODWARD, S. M., and C. J. POSEY, Hydraulics of steady flow in open channels, John Wiley, 1941.

Branch of Design and Construction,
Bureau of Reclamation,
Denver, Colorado

(Manuscript received March 19, 1951; presented at the Thirty-Second Annual Meeting, April 30, 1951; open for formal discussion until March 1, 1952.)

Transactions, American Geophysical Union Volume 32, Number 5 October 1951

PROPAGATION OF ELASTIC WAVES IN A FLOATING ICE SHEET

Frank Press and Maurice Ewing

Abstract--The characteristic equation for the propagation of elastic waves in a floating ice sheet is derived and discussed, with special emphasis on the evaluation of phase velocity for very large and very small wavelengths. The solutions cannot be reduced to symmetric and antisymmetric modes as in the case of a plate in a vacuum or a liquid. Among the waves discussed are compressional, shear, longitudinal, flexural, Rayleigh, Stoneley, and Love waves.

Introduction--This paper was undertaken as a result of interest in the utilization of elastic waves transmitted through a floating ice sheet for determining the thickness and mechanical strength of the ice, for position fixing, and long-range signaling. The ice sheet is treated as a two-dimensional wave guide, and the characteristic equation giving the functional dependence between phase velocity and period is derived. From an examination of this equation one can identify the possible waves and determine whether or not they are attenuated. In the derivations which follow the atmosphere is replaced by a vacuum. Air coupling of flexural waves in floating ice has been treated in other papers by PRESS, CRARY, OLIVER, and KATZ [1951] and by PRESS and EWING [1951].

Infinite plate in a vacuum and liquid--The analogous problems of wave propagation in an infinite elastic plate were solved by LAMB [1917] for a plate in a vacuum and by OSBORNE and HART [1945] for a plate in a liquid having infinite extent and considerably smaller sound velocity than that for compressional or shear waves in the plate. These writers did not include SH waves (shear waves polarized horizontally) in their solutions, but fully discussed all other elastic wave types.

In the solutions of Lamb and of Osborne and Hart the period equations take the form of fourth- and sixth-order determinants respectively. These reduce respectively to two second- and third-order determinants representing motions of the plate which are symmetrical and antisymmetrical about the median plane. For wavelengths small compared to the thickness of the plate the symmetric and antisymmetric solutions reduce to Rayleigh waves transmitted along the surfaces. These surface waves are attenuated for the case of a plate in a liquid because of losses by acoustic radiation. For short wavelengths there is also a Stoneley-type wave traveling along the plate-liquid interfaces with a velocity close to, but less than, the velocity of sound in the liquid.

For wavelengths large compared to the thickness of the plate the antisymmetric solution reduces to flexural waves and the symmetric solution becomes longitudinal waves of an elastic plate. The effect of the liquid on the propagation of the longitudinal waves is to add a small attenuation which increases as the frequency. The flexural waves, traveling with a velocity less than the speed of sound in the liquid, remain unattenuated in the presence of the liquid, although the dispersion is somewhat changed. For long wavelengths the presence of the liquid introduces an additional solution for the symmetric case in which the waves are propagated without attenuation with a velocity very close to that of sound in the liquid.

For intermediate wavelengths, solutions exist for the plate in a liquid which are closely related to the corresponding solutions for a plate in a vacuum. The effect of the liquid is to introduce attenuation caused by radiation loss for those branches in which phase velocity exceeds the speed of sound in the liquid. The presence of a liquid introduces two additional branches representing unattenuated propagation at velocities less than the speed of sound in the liquid.

Floating ice sheet--The theory of elastic waves in a floating ice sheet will now be discussed in greater detail. The procedure will follow that of Lamb and of Osborne and Hart, whose solutions were used as a basis for solving the present problem.

Let us consider the propagation of elastic waves in an infinite, floating ice sheet of thickness 2H, density ρ_1, in which the velocities of compressional and distortional waves are respectively α_1 and β_1. The underlying liquid having density ρ_2 and compressional wave velocity v_2 is taken to be infinitely deep. λ_1, μ_1 are Lamé's constants for the ice and λ_2 is the incompressibility of the liquid related to the elastic wave velocities as follows.

$$\alpha_1^2 = (\lambda_1 + 2\mu_1)/\rho_1 \qquad \beta_1^2 = \mu_1/\rho_1 \qquad v_2^2 = \lambda_2/\rho_2 \quad \ldots\ldots\ldots\ldots (1)$$

The cartesian coordinate system is chosen with the x-axis in the median plane of the ice sheet parallel to the direction of propagation and the z-axis vertically downward. The subscripts 1 and 2 refer to the ice and liquid respectively. We introduce the functions ϕ (x,z,t) and ψ (x,z,t) defined by the equations

$$\left.\begin{aligned} u_1 &= \partial\phi_1/\partial x + \partial\psi_1/\partial z \\ w_1 &= \partial\phi_1/\partial z - \partial\psi_1/\partial x \\ u_2 &= \partial\phi_2/\partial x \\ w_2 &= \partial\phi_2/\partial z \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where u and w are the horizontal and vertical particle displacements. SH waves are not included in this discussion and will be treated more simply in a later section. The vertical stress p_{zz} and the tangential stress p_{xz} can be expressed in terms of ϕ, ψ and the elastic constants as follows.

$$\left.\begin{aligned} p_{zz} &= \lambda\nabla^2\phi + 2\mu(\partial^2\phi/\partial z^2 - \partial^2\psi/\partial x\partial z) \\ p_{xz} &= \mu(\partial^2\psi/\partial z^2 - \partial^2\psi/\partial x^2 + 2\,\partial^2\phi/\partial x\partial z) \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots (3)$$

It is required that the functions ϕ and ψ satisfy the wave equations

$$\left.\begin{aligned} \partial^2\phi_1/\partial t^2 &= \alpha_1^2\nabla^2\phi_1 \quad \text{in the ice} \\ \partial^2\psi_1/\partial t^2 &= \beta_1^2\nabla^2\psi_1 \quad \text{in the ice} \\ \partial^2\phi_2/\partial t^2 &= v_2^2\nabla^2\phi_2 \quad \text{in the liquid} \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots (4)$$

and the boundary conditions

$$\left.\begin{aligned} (p_{zz})_1 &= 0 && \text{at } z = -H \\ (p_{zx})_1 &= 0 && \text{at } z = -H \\ (p_{zz})_1 &= (p_{zz})_2 && \text{at } z = H \\ (p_{zx})_1 &= 0 && \text{at } z = H \\ w_1 &= w_2 && \text{at } z = H \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots\ldots (5)$$

It can readily be verified that solutions of (4) are of the form

$$\left.\begin{aligned} \phi_1 &= [A\sinh(\xi z) + B\cosh(\xi z)]\exp[i(kx - \omega t)] \\ \psi_1 &= [C\sinh(\eta z) + D\cosh(\eta z)]\exp[i(kx - \omega t)] \\ \phi_2 &= E\exp(-\zeta z)\exp[i(kx - \omega t)] \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots (6)$$

where

$$\left.\begin{aligned} \xi^2 &= k^2(1 - c^2/\alpha_1^2) \\ \eta^2 &= k^2(1 - c^2/\beta_1^2) \\ \zeta^2 &= k(1 - c^2/v_2^2) \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots\ldots\ldots (7)$$

and $c = \omega/k$. In (6), ϕ_1, ψ_1, and ϕ_2 make up a system of waves progressing in the x-direction with a phase velocity c and wavelength L related to the wave number k by $k = 2\pi/L$. The frequency f is given by $f = \omega/2\pi = ck/2\pi$. ϕ_2 is taken to decrease exponentially with depth in the liquid since we are particularly interested in the case where no energy is lost by refraction into the liquid.

If equations (6) are substituted in the boundary conditions (5), using (2) and (3), five independent homogeneous equations in the unknown amplitude coefficients A, B, C, D, E, are obtained. Any four of the unknowns can be found in terms of the fifth. For a solution of all five to exist, however, the fifth-order determinant of their coefficients must vanish. The characteristic equation is the condition for the determinant to vanish. Poisson's assumption is made at this point to simplify our equations. Thus we take Poisson's constant $\sigma = 0.25$ for ice, so that $\lambda_1 = \mu_1$. Although observed values of σ for lake ice run higher, the simplification involved justifies this assumption since we are interested primarily in identifying the possible waves and only order of magnitude calculations are made. The period equation can then be written

$$P\,[Q + \delta \cosh(\xi H)\cosh(\eta H)] + Q\,[P + \delta \sinh(\xi H)\sinh(\eta H)] = 0 \quad \ldots\ldots (8)$$

where

$$\left.\begin{aligned} \delta &= \rho_2 v_2^2 (\eta^2 - k^2)(\xi^2 - k^2)\,\xi/\rho_1 \beta_1^2 \\ Q &= (\eta^2 + k^2)^2 \sinh(\xi H)\cosh(\eta H) - 4\xi\eta k^2 \cosh(\xi H)\sinh(\eta H) \\ P &= (\eta^2 + k^2)^2 \cosh(\xi H)\sinh(\eta H) - 4\xi\eta k^2 \sinh(\xi H)\cosh(\eta H) \end{aligned}\right\} \quad \ldots\ldots (9)$$

If these equations are compared to the characteristic equations given by Lamb, it will be seen that $P = 0$ and $Q = 0$ represent respectively the symmetric and antisymmetric solutions for a plate in a vacuum. Osborne and Hart obtained for the case of a plate in a liquid $P + \delta \sinh(\xi H)\sinh(\eta H) = 0$ and $Q + \delta \cosh(\xi H)\cosh(\eta H) = 0$ which represent respectively the symmetric and antisymmetric solutions. It is evident that unlike these cases, the motion in a floating ice sheet cannot be reduced to purely symmetric and antisymmetric modes. It can also be seen that δ is a correction term introduced by the presence of the liquid, and vanishes as the density of the liquid approaches zero.

The period equation (8) defines an implicit relation between the phase velocity c and the wave number k. The dependence of c on ω can be obtained by substituting $k = \omega/c$ in (8). Real values of c and k which satisfy (8) correspond to propagation without attenuation. Complex values of c or k for real ω correspond to propagation with attenuation, the degree of attenuation increasing with the magnitude of the imaginary component. The energy loss associated with damped propagation is due to radiation from the ice sheet into the liquid.

From (8) it is seen that $c = \alpha_1$ and $c = \beta_1$ are solutions which satisfy the characteristic equation for all frequencies.

Evaluation of phase velocity for very small wavelengths--For wavelengths small compared to the thickness of the ice sheet (kH large) P = Q and (8) reduces to

$$(\eta^2 + k^2)^2 - 4\xi\eta k^2 = 0 \quad \ldots\ldots (10)$$

and

$$(\eta^2 + k^2)^2 - 4\xi\eta k^2 + \delta = 0 \quad \ldots\ldots (11)$$

Equation (10) is the same expression derived by Lamb for a plate in a vacuum and corresponds to Rayleigh waves propagated along the free surface of a semi-infinite solid medium. The algebraic solution of (10) for c gives the well-known result for Rayleigh waves $c_R = 0.9194\,\beta_1$. Equation (11) is identical to the expression derived by Osborne and Hart for a plate in a liquid and corresponds to Rayleigh waves propagated along the interface between a semi-infinite liquid and solid medium. Following Osborne and Hart the phase velocity can be deduced approximately from (11) by substituting $c = c_R(1 + \epsilon)$, $(\epsilon < 1)$ in (11). If δ is small, we may write approximately

$$\epsilon = -i\,[(\rho_2/\rho_1)(1 - c_R^2/\alpha_1^2)^{0.5}\, c_R^4/\beta_1^4]/4(c_R^2/v_2^2 - 1)^{0.5}\left\{2(1 - 0.5\,c_R^2/\beta_1^2)\,c_R^2/\beta_1^2 - [(1 - c_R^2/\beta_1^2)/(1 - c_R^2/\alpha_1^2)]^{0.5} c_R^2/\alpha_1^2 - [(1 - c_R^2/\alpha_1^2)/(1 - c_R^2/\beta_1^2)]^{0.5} c_R^2/\beta_1^2]\right\} \ldots (12)$$

Using $\rho_1 = 0.917\,\rho_2$, $\beta_1 = 6300$ ft/sec, $v_2 = 4800$ ft/sec, $\alpha_1 = \sqrt{3}\,\beta_1$, we obtain approximately $\epsilon = 0.25\,i$.

The reduction of the period equation (8) into the algebraic expressions (10) and (11) for wavelengths small compared to the plate thickness is simply interpreted. For these wavelengths, the ice sheet is effectively infinitely thick and the propagation reduces to Rayleigh waves propagated without attenuation at the free surface and attenuated Rayleigh waves transmitted along the bottom surface, continuously radiating energy to the liquid.

Equation (11) can also be satisfied by c real and less than v_2. This can be seen by rewriting (11) in the form

$$(1 - c^2/v_2^2)^{0.5}\,[(2 - c^2/\beta_1^2)^2 - 4(1 - c^2/\alpha_1^2)^{0.5}(1 - c^2/\beta_1^2)^{0.5}] + (1 - c^2/\alpha_1^2)^{0.5}\,\rho_2 c^4/\rho_1\beta_1^4 = 0 \quad \ldots \quad (13)$$

The first and second terms of (13) are of opposite sign, so that c less than v_2 is a possible solution. For the constants listed above we obtain $c = 0.87\ v_2$ as a root of (13). This is the speed of a boundary wave traveling along the ice-water interface, with an amplitude which decreases with distance from the ice-water interface. STONELEY [1924] described an analogous boundary wave which can be transmitted under certain conditions along the interface between two semi-infinite solids.

Evaluation of phase velocity for very large wavelengths--For wavelengths which are long compared to the thickness of the ice sheet (kH small), (8) can be reduced to

$$P + Q\delta \sinh(\xi H)\sinh(\eta H)/2Q + \delta = 0 \quad \ldots \quad (14)$$

$$Q + \delta/2 = 0 \quad \ldots \quad (15)$$

Equations (14) and (15) will give respectively the velocities of longitudinal waves and flexural waves in a floating ice sheet over deep water. The factor $\sinh(\xi H)\sinh(\eta H)$ is neglected in (15) and carried in (14) in order to keep the high-order imaginary term giving the attenuation of longitudinal waves. Replacing the hyperbolic functions of (14) by linear terms or unity we can derive the approximate expression

$$c/\beta_1 = 2(1 - \beta_1^2/\alpha_1^2)^{0.5}\left\{1 + i(kH)^3(2\beta_1/v_1)(\rho_1/\rho_2)(1 - \beta_1^2/\alpha_1^2)^{0.5}[1 - (1 - \beta_1^2/\alpha_1^2)4\beta_1^2/\alpha_1^2]\right\}. \quad (16)$$

If (16) is compared with the solution $c/\beta_1 = 2(1 - \beta_1^2/\alpha_1^2)^{0.5}$ for a plate in a vacuum, it is seen that the presence of the liquid hardly affects the real part of the phase velocity, but adds a small attenuation, which for large wavelengths increases as the inverse cube of wavelength. This is in agreement with the experimental work of EWING, CRARY, and THORNE [1934] whose determination of the velocity of longitudinal waves in floating lake ice checks the velocity given by the real part of (16).

For long wavelengths, (15) gives for the velocity of flexural waves

$$c^2/\beta_1^2 = (8/3)(\rho_1/\rho_2)(kH)^3(1 - \beta_1^2/\alpha_1^2)/(1 + 2\,kH\rho_1/\rho_2) \quad \ldots \quad (17)$$

In obtaining (17), third-order terms must be included in the expansion of the hyperbolic functions. For a plate in a vacuum the corresponding solution is $c^2/\beta_1^2 = (4/3)(kH)^2(1 - \beta_1^2/\alpha_1^2)$. It is interesting to note that (17) can be reduced to the corresponding expression for a plate in a liquid simply by replacing ρ_2 by $2\rho_2$.

The steady-state, plane wave theory of long flexural waves in an ice sheet on water of either finite or infinite depth was given by EWING and CRARY [1934]. The results for the latter case were extended by PRESS and EWING [1951] for waves originating in an impulsive point source. The observed dispersion and amplitude of explosion generated flexural waves on lake ice are shown to be in reasonable agreement with theory in these papers. At certain frequencies flexural waves in ice are strongly coupled to the atmosphere. This phenomenon has been discussed by PRESS, CRARY, OLIVER, and KATZ [1951] and PRESS and EWING [1951].

Evaluation of phase velocity for intermediate wavelengths--Unlike the results for a plate in a vacuum or a liquid, the characteristic equation does not reduce to symmetric and antisymmetric modes. We are left with a complicated expression, equation (8), which makes the evaluation of phase velocity as a function of wavelength or frequency an exceedingly difficult task for intermediate wavelengths. Such calculations would indicate how the high and low frequency values of phase velocity discussed above connect up. In general for $c > v_1$, the phase velocity has an imaginary

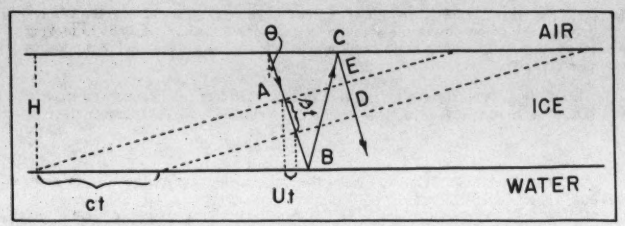


Fig. 1--Ray-path diagram of SH-waves in an ice sheet on water

component, indicating attenuation due to radiation from the sheet into water. Both real and imaginary components of phase velocity are frequency dependent, the waves being dispersive as well as selectively attenuated. For $c < v_1$, no energy losses due to radiation into the water occur and the waves are propagated as a dispersive, unattenuated train.

Love waves in a floating ice sheet--The theory of Love waves in a floating ice sheet can be derived by finding a solution of the wave equation for SH waves which satisfies appropriate boundary conditions. It is convenient and instructive, however, to derive the characteristic equation geometrically, for this method offers a clear physical picture of its origin.

SH waves incident on a free surface or a liquid interface are completely reflected without a change of phase; see, for example, JEFFREYS [1925]. Consequently, a floating ice sheet behaves essentially as a wave guide for the propagation of SH waves. In Figure 1, ABCE represents the ray-path of a plane SH wave of length ℓ (measured along the ray-path) undergoing multiple reflections from the boundaries at an angle of incidence θ. As the wave front (shown by the dashed line) moves a distance $ED = \beta_1 t$ in t seconds, a point on the wave front moves a distance ct in the horizontal direction where the phase velocity $c = \beta_1/\sin\theta$. After many reflections the amplitude will be greatest for those waves for which constructive interference occurs between the multiple reflected rays. The characteristic equation is simply the mathematical statement of this condition. Referring to Figure 1 again, it is seen that if the wave front at AE is to interfere constructively with the coincident wavefront which has traversed the additional path ABCE, it is required that

$$\overline{ABCE} = 2H\cos\theta = n\ell \qquad n = 1, 2, 3 \ldots\ldots\ldots\ldots \qquad (18)$$

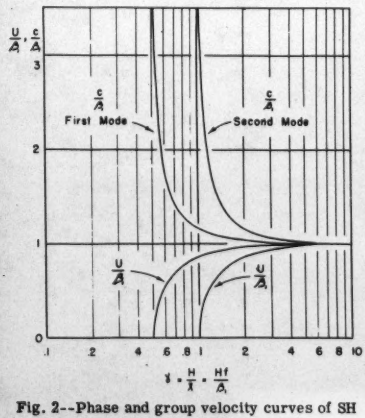


Fig. 2--Phase and group velocity curves of SH waves in an ice sheet on water

The integers n determine the normal modes of propagation. For each value of n, there is a fixed relationship between ℓ and θ (or c) for which constructive interference occurs. The propagation of constructively interfering SH waves is dispersive, the dependence of phase velocity on wavelength being given by (18) and $c = \beta_1/\sin\theta$. A consequence of dispersion is that the energy associated with each frequency is propagated with the group velocity U given by the well-known formula $U = c + k\,dc/dk = c + k\,(dc/d\theta)\,(d\theta/dk)$, where $k = (2\pi/\ell)\sin\theta$ is the wave number. Carrying out the indicated differentiation one obtains

$$U = \beta_1 \sin\theta = \beta_1^2/c \qquad \ldots\ldots (19)$$

U/β_1 and c/β_1 are plotted for the first and second modes as functions of the dimensionless parameter $\gamma = H/\ell = Hf/\beta_1$ in Figure 2. The higher modes of Love waves are simply higher harmonics of the first or fundamental mode.

*The sequence of waves arriving at a given point from a distant disturbance can be described with the aid of the group velocity curve

of Figure 2. The first arrivals are high frequency waves which travel with the velocity β_1. As time progresses the frequency of the arrivals decreases. This corresponds to moving down the group velocity curve. The wave train is infinitely long, the last wave having the lowest frequency given by $f_c = {}_1/2H$.

Acknowledgment--The research resulting in this work has been sponsored in part by the Geophysical Research Directorate of the Air Force Cambridge Research Laboratories.

References

EWING, MAURICE, and A. P. CRARY, Propagation of elastic waves in ice, II, Physics, v. 5, pp. 181-184, 1934.

EWING, MAURICE, A. P. CRARY, and A. M. THORNE, JR., Propagation of elastic waves in ice, I, Physics, v. 5, pp. 165-168, 1934.

JEFFREYS, HAROLD, The reflection and refraction of elastic waves, Mon. Not. R. Astron. Soc., Geophys. Sup., v. 1, pp. 282-292, 1925.

LAMB, HORACE, On elastic waves in a plate, Proc. R. Soc. London, v. A93, p. 114, 1917.

OSBORNE, M F. M., and S. D. HART, Transmission, reflection, and guiding of an exponential pulse by a steel plate in water, I, Theory, J. Acoust. Soc. Amer., v. 17, pp. 1-18, 1945.

PRESS, FRANK, A. P. CRARY, JACK OLIVER, and SAMUEL KATZ, Air-coupled flexural waves in floating ice, Trans. Amer. Geophys. Union, v. 32, pp. 166-172, 1951.

PRESS, FRANK, and MAURICE EWING, Theory of air-coupled flexural waves, J. Appl. Physics, v. 22, pp. 892-899, 1951.

STONELEY, ROBERT, The elastic waves at the surface of separation of two solids, Proc. R. Soc. London, v. A106, pp. 416-428, 1924.

Lamont Geological Observatory (Contribution No. 38),
Columbia University,
Palisades, New York

(Communicated manuscript received January 17, 1951;
open for formal discussion until March 1, 1952.)

A PHOTOGRAPHIC STUDY OF CHANGES OF THE INFRARED EMISSION OF THE POLAR AURORA

L. Herman and H. Leinbach

Abstract--Pairs of pictures of the aurora taken simultaneously on a panchromatic film through a green filter and on an infrared film through a red filter sometimes show a striking enhancement of the infrared emission with the passage of time. The paper gives the results of a semi-quantitative comparison of two different sequences of such pictures, made at College, Alaska.

Visual observations of strong auroral displays often show that striking changes of color occur, particularly in the rayed bands and draperies. The most notable change at high latitudes is the appearance of a red lower edge, the type-B aurora, caused by the enhancement of the first positive system of N_2. Spectrographic studies of such changes are difficult to make with the spectrographs usually available. Spectra obtained on long exposures generally do not show important differences; the ordinary type aurora gives the greatest contribution and masks any changes in the spectrum due to the short-lived enhancements.

In order to study such rapid changes, a method involving simultaneous exposures with two cameras was adopted. Two 35-mm "Robot" cameras with f/1.9 lenses were mounted on the same tripod, one with a Wratten type XI green filter, and the other with a Wratten type A red filter. Super XX film was used in the former, and non-sensitized NI infrared film in the latter camera. The apparent spectral sensitivity of the Super XX film used with the XI filter is 25 pct of the incident light at 6000 A and ten per cent at 6400 A. The effective wave-length interval used lies between 4900 A and 5700 A. Type NI film has a very low sensitivity below 6800 A and cuts off sharply at about 9000 A. The Wratten type A filter has negligible transmission at 5800 A and transmits better than 80 pct at 6200 A. The exposure time was the same for both cameras and the films were developed the same length of time in D-72 developer.

About 200 pairs of pictures were obtained during March 1951. Most of the common auroral forms are represented, the exceptions being the faint diffuse surfaces and the pulsating surfaces.

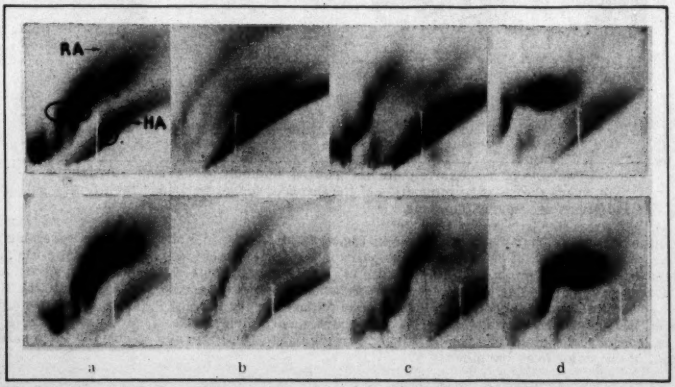


Fig. 1--Two sets of successive pictures showing a strong increase of the infrared emission of a homogeneous arc HA compared to a rayed arc RA; the upper is the infrared set and the lower the green set; the positions of the areas measured photometrically on each picture are shown by the circles on a of the infrared series

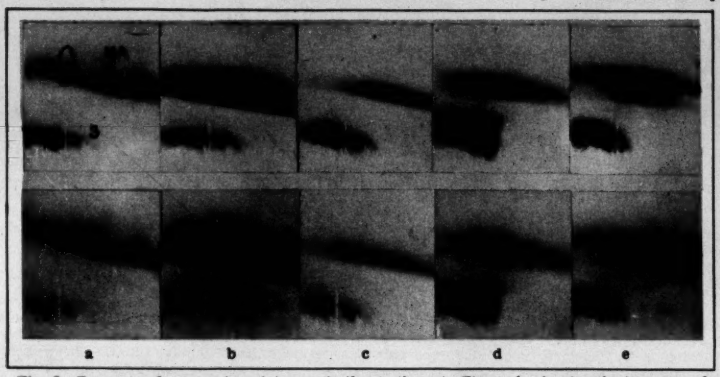


Fig. 2--Two sets of successive pictures similar to those in Figure 1, showing the increase of the infrared emission of a surface S compared to a homogeneous arc HA; the upper is the infrared set and the lower the green set; the positions of the areas measured photometrically on each picture are shown by the circles on a of the infrared series

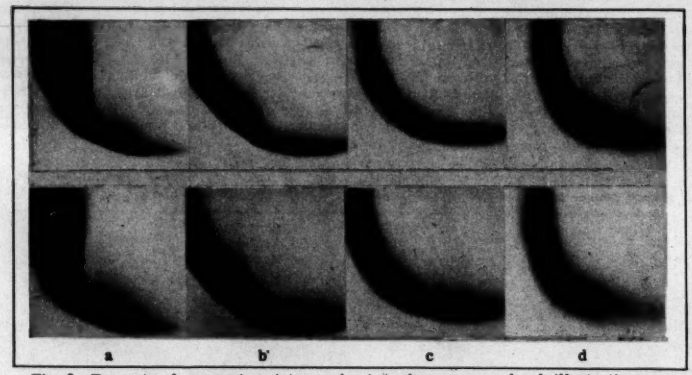


Fig. 3--Two sets of successive pictures showing a homogeneous band, illustrating a case where the relative intensities of the infrared (upper set) and green (lower set) radiations are nearly the same

Some examples of such pairs are shown in Figures 1, 2, and 3. All of these pairs were taken with exposures of about one minute. The pairs in a given sequence were taken at intervals of about one and a half minutes. The sequence of pictures in Figure 1 shows both a rayed arc and a homogeneous arc. The homogeneous arc shows a striking enhancement in relation to the rayed arc in the infrared when compared to the same pictures in the green. Figure 2 shows a similar case, the infrared again showing a relative enhancement which changes from pair to pair. Figure 3 is a sequence of pictures taken of a homogeneous band. Here there is apparently little enhancement of one color over the other.

A semi-quantitative study was made of the pairs shown in Figures 1 and 2. Calibration films were taken in the laboratory using the same film and filters as used on the aurora. The characteristic curves of the infrared film and the Super XX film possess nearly the same contrast factor gamma. This makes it easy to find out, by a simple visual examination, the relative changes of the infrared emission in a given sequence. Tables 1 and 2 show the measured relative increase of

Table 1--Relative intensity ratios of the infrared and green pictures in Figure 1

Paired figures	Relative intensities				I_{RA}/I_{HA}	
	Green		Infrared			
	I_{HA}[f]	I_{RA}[g]	I_{HA}	I_{RA}	Green	Infrared
a	1.23	1.81	1.33	1.17	1.47	0.88
b	1.62	1.35	2.05	0.67	0.83	0.33
c	1.52	1.55	3.02	1.27	1.02	0.42
d	1.00	2.14	1.00	1.27	2.14	1.27

[f]Intensity of the homogeneous arc.
[g]Intensity of the rayed arc.

Table 2--Relative intensity ratios of the infrared and green pictures in Figure 2

Paired figures	Relative intensities				I_S/I_{HA}	
	Green		Infrared			
	I_S[h]	I_{HA}[f]	I_S	I_{HA}	Green	Infrared
a	0.63	0.70	0.50	0.38	0.90	1.32
b	0.56	1.10	0.45	0.81	0.51	0.56
c	0.67	0.73	1.23	0.29	0.92	4.24
d	1.24	0.73	1.48	0.35	1.70	4.23
e	1.00	0.75	1.00	0.46	1.34	2.18

[f]Intensity of the homogeneous arc.
[h]Intensity of the surface.

the infrared as compared to the green for the sequences in Figures 1 and 2. A comparison of the progressive change of the intensity ratios in last two columns of each table gives a measure of the enhancement of the infrared emission along the sequences of pictures. It must be remembered that for a given pair the different absorption coefficients because of scattering of the green and of the infrared may cause an apparent enhancement of the infrared, especially when the display is near the horizon. However, the absorption by scattering could not account for changes of the relative enhancements of one pair as compared to another in the same sequence. Thus, in some auroral forms, we find a strong increase of the infrared emission as compared to the green spectral region.

As observations show, there are many different forms of the aurora, caused by different conditions of excitation. The low altitude aurora, as previously mentioned, often show enhancement of the first positive system of N_2. It is this type aurora that is probably represented in Figures 1 and 2. The high-altitude aurora, on the other hand, show enhancement of the forbidden oxygen lines at 6300 A and 6364 A, of the green line of NI at 5198 A, and of the Vegard-Kaplan bands $A^3\Sigma_u^+ \rightarrow X\ ^1\Sigma_g^+$ of N_2. An infrared spectrum, taken with a grating spectrograph and a high aperture camera, is shown in Figure 4. The main components of this spectrum are: the first positive system $B^3\Pi_g \rightarrow A^3\Sigma_u^+$ of neutral nitrogen; a new band system probably emitted by neutral nitrogen (a laboratory study of these new bands has been made and the results will be published in a separate paper); the forbidden Kaplan-Meinel atmospheric band (0,1) of O_2 at 8625 A; and the permitted lines of oxygen and nitrogen. These are the principal radiations that may be affecting the infrared pictures. The band pass of the infrared filter is so broad that it is not possible to tell which molecules or atoms are responsible for the enhancements shown in the figures.

The sequence of pictures in Figures 1 and 2 does not seem to indicate a change in the basic form of the aurora. The main reason for such big changes in the spectral distribution of light is probably either a modification of the electrical conditions of the gas (concentrations of the ions and electrons) or a change in the speed of the exciting particles. Another possibility is the presence of an afterglow, and its relative enhancement after the passage of the electrical exciting particles.

The observations outlined above indicate that, with the equipment used, noticeable changes can be detected on about five per cent of the pictures taken, covering most of the auroral forms. Even this low percentage would make it seem worth while to elaborate on the program, using the

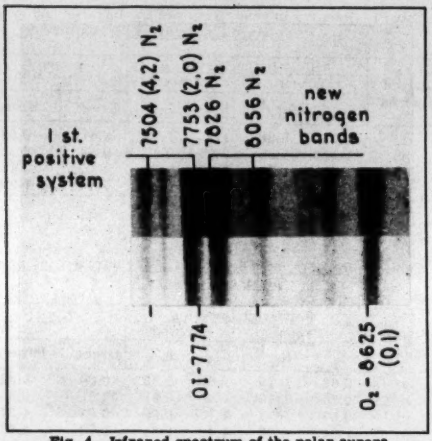


Fig. 4--Infrared spectrum of the polar aurora

fastest lenses available, with narrow band pass filters. It seems reasonable to assume that the percentage of pictures showing enhancements would increase if shorter time exposures could be used. It is also apparent that such pairs are more meaningful when a sequence of the same region is taken.

Acknowledgments--This work was supported in part by Contract No. AF19(122)-431 with the U. S. Air Force, through sponsorship of the Geophysical Research Directorate of the Air Force Cambridge Research Laboratories. L. Herman is on leave from the Astrophysical Observatory of the University of Paris.

Geophysical Institute,
University of Alaska,
College, Alaska

(Communicated manuscript received April 26, 1951;
open for formal discussion until March 1, 1952.)

Transactions, American Geophysical Union Volume 32, Number 5 October 1951

ON HIGH-LEVEL CYCLONES ORIGINATING IN THE TROPICS

C. E. Palmer

Abstract--Two weather situations, one in June 1946 and another in March 1949, suggest that cyclonic circulations may originate in the high tropical troposphere (above 30,000 ft and between 15° N and 10° N) and remain stationary as long as two weeks while extending downward to 20,000 ft or less. They may then move out of the tropics into higher latitudes where they appear on 500-mb or lower contour maps as "cold lows" similar to those described by Palmén.

Previous work--The hope, entertained by our immediate predecessors in synoptic meteorology, that extension of scientific observation to the upper part of the troposphere would give us not only greater empirical knowledge of the motion and composition of the atmosphere, but also an increased power to predict changes in those fields, has in recent years been justified by discoveries that could not have been anticipated 50 years ago. Outstanding among the unexpected discoveries is that of the existence, in the horizontal wind fields above 20,000 ft, of cyclonic circulations which have virtually imperceptible correlates in the lower tropospheric wind patterns but which, nevertheless, are accompanied by extensive sheets of cloud and precipitation on to the ground. While credit must be given for contributions to this discovery to SWERDTFEGER [1948], CROCKER, GODSON, and PENNER [1947], and to many workers in the U. S. Weather Bureau and in European Weather Services, the clearest and most profound exposition of it is contained in the writings of PALMÉN [1949]. In describing the high-level cyclones of middle latitudes in North America, Palmén has placed great emphasis on the process by which such a circulation may be established in a pool of cold air, which, after its passage from high latitudes into the south (25° - 35° N), becomes "cut off" from its parent current by differential subsidence. The stages of the process are so evident on North American upper-level maps and are so readily identified by the professional meteorologist during routine analysis of that region that a tendency has developed to attribute a similar origin to all upper-level cyclones, wherever they might be found, and however much lack of dense observations might obscure their earlier history.

The tendency to generalize the description of Palmén to all cold lows aloft has been particularly unrestrained in those field forecasters who have had to deal with certain storms typical of the winter atmospheric regime west of the Hawaiian Islands. When these storms affect the surface circulation, they are sometimes known as "kona" storms, the native word "kona" referring to local peculiarities in wind direction on the islands affected by bad weather. But cloud and precipitation on the islands may also be associated with upper cold lows which leave the lower trade-wind circulation relatively undisturbed. In any case, a true "kona" storm at the surface seems to be the last stage in the development of a cyclonic circulation which is first detected on maps at or above 500 mb and which extends slowly downward, over a period of many days, until it is noticeable on the surface map.

Since there is no doubt that many upper-level cold lows originate in the manner described by Palmén, and since in this paper I will distinguish from them another species of upper-level circulation which may be important in the genesis of "kona" storms, I shall reserve the phrase "of polar origin" for lows which are unequivocally of the type already recognized in the literature. The phrase "of polar origin" is not intended to imply that the lows actually originate in polar regions, but merely that they appear to form in the upper part of an air mass, usually called "polar," that has moved from higher to lower latitudes.

The circulations to be described here differ from those of polar origin in the following respects: (a) They originate above 30,000 ft in very low latitudes. (b) They may remain stationary in the tropics for very long periods. (c) It is suggested here that they finally move north-eastward or east-north-eastward into the latitude belt 20°-30° N and may there again remain stationary for long periods. (d) During the passage toward higher latitudes they usually increase in intensity. For such lows I would propose the attribute, "of tropical origin."

The month of June 1946--Owing to the location of Operation Crossroads, upper-wind observations over the Marshall Islands during the months of June and July 1946 were unusually dense in

space and time and were supplemented by the excellent weather and wind data collected by aircraft of the U. S. Armed Forces on weather reconnaissance. The data have been analyzed by members of the Tropical Project, Institute of Geophysics, University of California, to whom acknowledgments are made elsewhere in this paper. The method of kinematic analysis used by the workers has been that of SANDSTROM [1909] and BJERKNES [1911]. At levels where aircraft winds obtained by drift methods were dense enough, the full isogon method was used; at higher levels, the streamlines were drawn freehand and the isovels, wherever any considerable doubt as to their course existed, were omitted. During a large part of the month of June 1946, the analysis revealed, the circulation in the upper troposphere over the Marshalls was dominated by a cyclonic circulation whose presence could not possibly be detected by a perusal of the lowest streamline analyses alone. Figure 1, for example, shows the analysis of the field of motion at 1500 ft over the Marshalls at 11h 00m Bikini time, June 10, 1946. The most prominent feature of the map is the wave-like perturbation of the streamlines south of 10° N. On June 9, this wave began to move into the area from the east; by the end of June 11 it had moved out of the region of dense observations toward the longitudes of the Marianas.

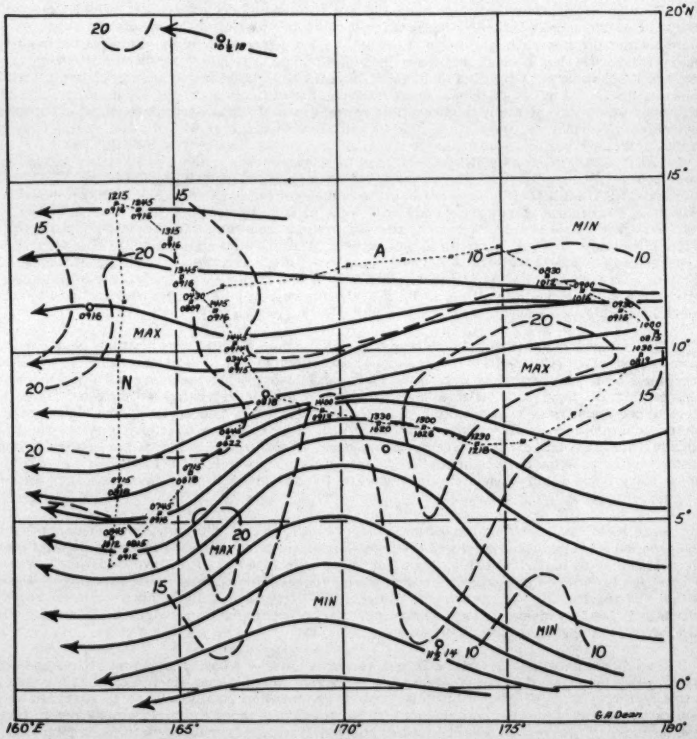


Fig. 1--Marshall Islands, wind field at 1500 ft, June 10, 1946, 11h 00m B; solid lines with arrows are streamlines; dashed lines, wind speed isopleths for each five knots

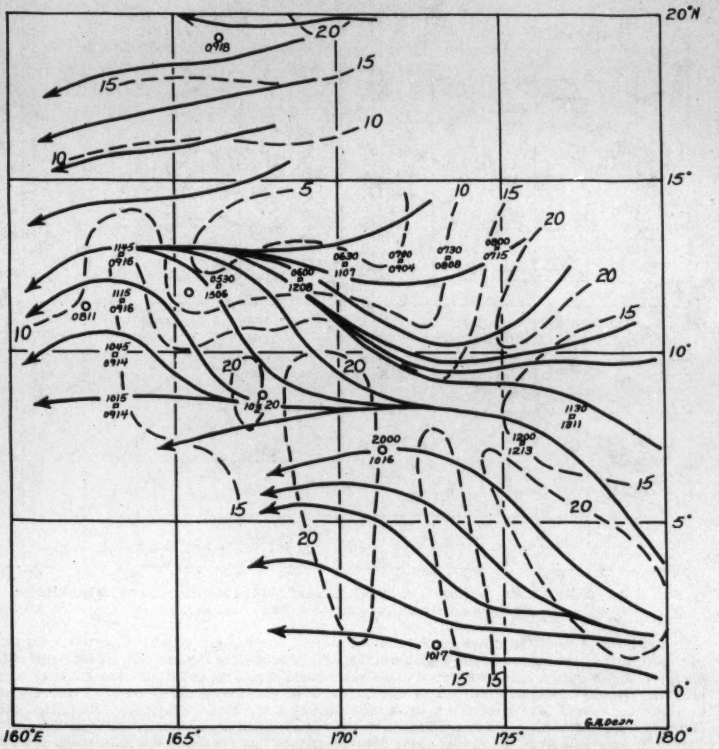


Fig. 2--Marshall Islands, wind field at 8000 ft, June 10, 1946, 11h 00m B; solid lines with arrows are streamlines; dashed lines, wind speed isopleths for each five knots

Figure 2 shows the cognate wind field at 8000 ft. While the southern, moving wave could still be detected at this level, another feature, very minor at 1500 ft and quasi-stationary in the field, became the dominating perturbation aloft. It lay north of 10° N and roughly about the longitude 165° E. As the analysis ascended to higher levels this quasi-stationary wave became more and more extensive horizontally, while the moving wave became harder to identify. Finally, at 30,000 ft, the Project workers found, the area occupied below by the quasi-stationary wave was the seat of an extensive cyclonic circulation, identifiable on Figure 3 as the surround of the cyclonic indraft singularity that is shown moving slowly south-eastward on maps (a) to (d). The whole analytic sequence for the period June 9-12 from the surface to 50,000 ft has many other interesting features; it has been fully presented by the Tropical Project [PALMER and Dean, 1950; LANDERS, 1950; DEAN, 1951]. The reader will find the data displayed and discussed in detail in the references cited, so that, taken in conjunction with the published Crossroads data [COMMANDER, JOINT TASK FORCE 1, 1947], the analyses may be checked at all points.

Three features of the cyclonic indraft are worthy of remark here. First, the lowest level at which it could be detected on June 9 and 10 as a singularity was 28,000 ft; above this level it per-

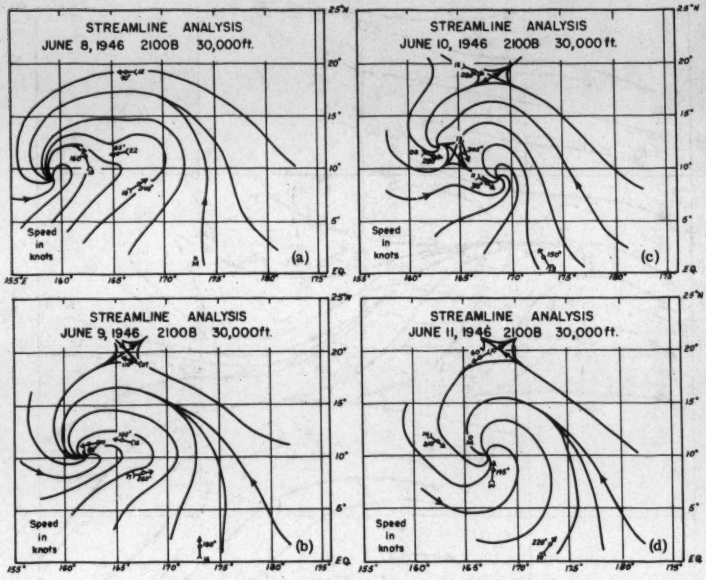


Fig. 3--Marshall Islands, wind field at 30,000 ft, June 8-11, 1946; solid lines, streamlines; arrows, wind direction in degrees, and speed in knots

sisted at least to 50,000 ft, observations above that height being too sporadic to permit analysis. Secondly, if the atmosphere in the region immediately surrounding the cyclonic indraft point differed in temperature from environmental air at the same level, the difference was so small as to be within the observational error. This was borne out by the analyses displayed in Figures 4 and 5, where an attempt has been made to draw the contours of the 300-mb surface. The plotted winds on these maps were at the heights indicated by the contours and hence they differ from those of Figure 3. So gentle were the slopes of the 300-mb surface that errors in the radiosonde observations, integrated to these levels, produced large and erratic shifts in the main contour depression, as compared with the slowly varying position of the cyclonic indraft point at 30,000 ft (marked on these maps with a cross). In a general way, we can see that the singularity is accompanied by a depression of the 300-mb surface but the contour errors do not permit us to rely on the details of the surface topography.

The most remarkable feature of the upper-level cyclone is the long period of its persistence. The first unequivocal sign of its presence in the Marshall Islands area occurred on June 5 at very high levels (above 40,000 ft); thereafter it remained over the observational network there until June 18, after which time it began to move toward the east-north-east. DEAN, MILLER, and STOPINSKI [1951] are publishing a detailed account of its structure during the period June 17-19 (Bikini date). Those who do not desire to study in detail the analytical intricacies may refer to the published Northern Hemisphere Historical Weather Maps [HEADQUARTERS, A. W. S., 1948] where between June 12 and 17 the disturbance appears at 500 mb.

The material presented here and in the references shows:

(a) Cyclonic circulations may originate in the upper part of the tropical troposphere.

(b) These circulations may appear first in the highest parts of the troposphere and gradually extend downward, at least to the 500-mb surface.

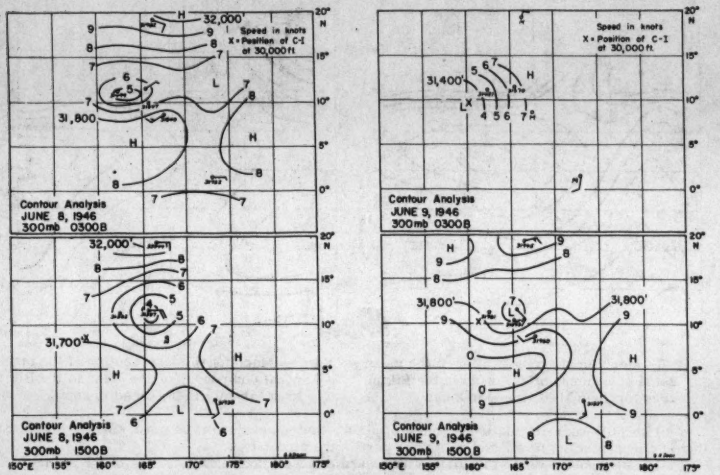


Fig. 4--Marshall Islands, 300 mb, June 8 and 9, 1946; solid lines, 100-ft contours; arrows, wind direction with barbs showing speed in knots; one long barb = 10 knots

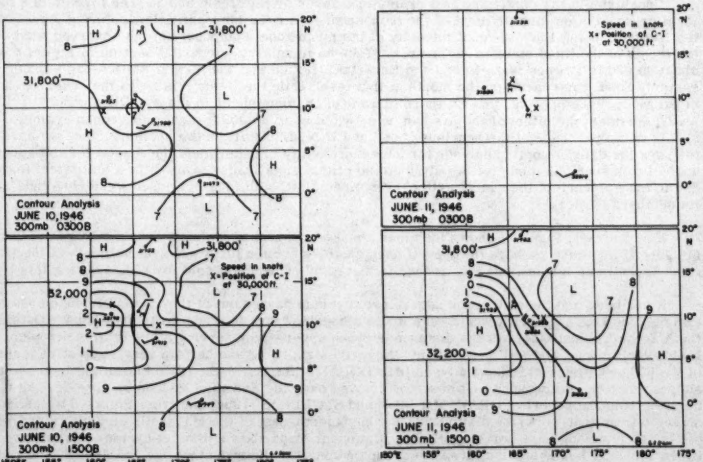


Fig. 5--Marshall Islands, 300 mb, June 10 and 11, 1946; solid lines, 100-ft contours; arrows, wind direction with barbs showing speed in knots; one long barb = 10 knots

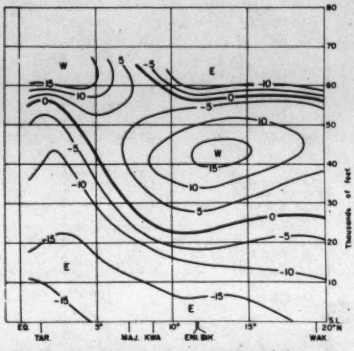


Fig. 6--Meridional cross-section of the mean zonal component of the wind in the Bikini area for June 1946; speed in knots

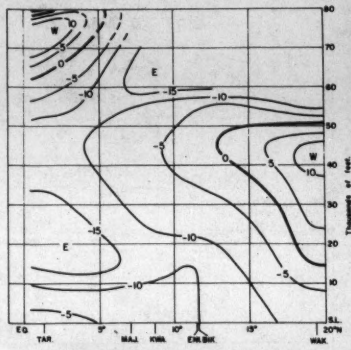


Fig. 7--Meridional cross-section of the mean zonal component of the wind in the Bikini area for July 1946; speed in knots

(c) Initially such circulations consist of air whose temperature is at most slightly lower than that at corresponding levels and not taking part in the circulation.

(d) The extension of the circulation downward is accompanied by a cooling of the air taking part in the motion, as compared with the air in its immediate environment.

(e) The circulations may remain quasi-stationary and centered at latitudes lower than 15°N for as long as two weeks.

Conclusion (e) is confirmed in a dramatic manner by Figures 6 and 7. The former is a meridional cross-section through most of the troposphere over the Marshall Islands during June 1946, the isopleths being lines of equal intensity of the mean zonal component of the observed winds for the month at the fixed stations in the area. Take an imaginary horizontal section in Figure 6 at about 25,000 ft between Wake Island and Eniwetok. Notice that the former station had a mean easterly zonal component for the month at that level while the latter, closer to the equator, had a mean westerly component, that is, there is a mean cyclonic shear in the zonal component at this level. Further, the effect of the low can be detected up to 50,000 ft, again as a mean cyclonic shear, in the presence of the spurious "jet" at 13° N, 42,000 ft, on the section. Since we have followed the daily synoptic analyses for June sufficiently to understand the reason for the appearance of this spurious mean jet, we attribute no causal significance to it. It is a statistical feature due to the presence of the quasi-stationary cyclone aloft, with long-continued westerly winds along its southern border.

For contrast, Figure 7 shows the mean zonal component of the wind over the Marshall Islands for July 1946. Here we have the typical deep easterly section for a wet season month in the tropics. There is no low latitude jet, neither is there any evidence of cold lows aloft during this month.

It has been mentioned that the upper-level cyclone passed out of the region of dense observation on June 18. A priori it would seem to be a hopeless task to trace its later history. Outside the Marshall Islands the average distance between upper-air observing stations in the tropical North Pacific was, and still is, 1000 mi. Nevertheless, there are certain very suggestive features of the 500-mb Historical Map analyses [HEADQUARTERS, A. W. S., 1948] that might lead one to suppose that the disturbance just described moved over the Hawaiian Islands on June 26. As may be seen from the report of DEAN, MILLER, and STOPINSKI [1951] and from Figure 8 which is abstracted from that work, the disturbance lay east-north-east of the Marshalls on June 18 and was presumably moving east-north-east. The Historical Maps show a distinct cyclonic circulation between Johnston Island and the Hawaiian group on June 22. Between that day and June 27 the wind at 500 mb over Honolulu turned gradually from east through south to west with a depression of the contour height over the same period from 19,160 to 18,970 ft and a total fall of temperature of about 2° C. On June 27 the observations unequivocally demand a closed depression north of Hawaii at 500 mb. A movement of the upper-level depression at 16 knots toward the east-north-east during the period would carry it into positions entirely consistent with the analyses of the Historical Series.

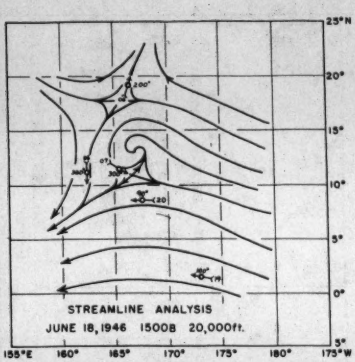


Fig. 8--Marshall Islands, wind field at 20,000 ft, June 18, 1946; solid lines, streamlines; arrows, wind direction in degrees, and speed in knots

The situation March 15-30, 1949--It is only on occasions like that of Operation Crossroads and of one or two very short periods during World War II that, over very limited areas, the density of observation permits unequivocal upper-air analysis in the tropics. Thus we can establish the facts outlined in the previous section within the Marshall Islands area, but as soon as the cyclone moves out of the region we can at best construct but not confirm hypotheses concerning its movement. Further, any knowledge we might gain about the movements of similar cyclones must at present come from a study of data and analyses similar to those of the Northern Hemisphere Series; a check of those so far published will show that the only tropical analyses that can be seriously considered are those attempted by the analysts of the Series for 1949, since before that time upper-wind data in low Pacific latitudes is almost completely lacking. If we take the facts of the last paragraph of the preceding section as suggesting a working hypothesis, namely, that it is possible for upper-level lows originating in the Marshall Islands to move into higher latitudes near the Hawaiian Islands, our task is to find in the 1949 data other evidence for such movements. We may take the period March 15-30, 1949 as an example. The only data referring to this period that are available to me are those of the teletype circuit "0", those on the Historical Maps [U. S. WEATHER BUREAU, 1950] (see Fig. 9), those published jointly by the U. S. Air Force, Army, Navy, and Weather Bureau [U. S. WEATHER BUREAU, 1949], and the Bulletins published by the Australian and New Zealand Governments [COMMONWEALTH WEATHER BUREAU, 1949; NEW ZEALAND METEOROLOGICAL SERVICE, 1949]. On the analyses displayed in Figures 10 to 14, wind data derived from the Historical Series alone and not from other sources are shown as dashed arrows. Compared with the network of observations obtainable from the North American continent and Europe, these data are sparse, so that it becomes an open question whether it is ever worth while attempting an upper-level analysis of tropical data other than that belonging to restricted times and places of unusual density, like Operation Crossroads. It has therefore been the contention of some workers on the Tropical Project that broad-scale analysis above 10,000 ft in the Pacific is to a large extent unprofitable. In deciding this question, however, remember that every upper-level analysis (and surface analysis, for that matter) is an interpolation, the attempt to fit a continuous field of some meteorological variable to a discrete set of point observations. A unique solution of the problem is only possible when the number of point observations is infinite, and then it is unnecessary. Even in the case of the networks of Europe and North America, more than one solution for a given set of observations is always possible; however, all the possible solutions will have certain general features in common, impressed upon them by the data. These common features, we may be sure, belong to the continuous field which is the true solution to the problem of interpolation. Now the number of possible qualitatively different solutions will increase as the data become sparser, until, of course, when there are no data there are infinitely many such solutions. But as long as there are observations the common features of all the possible solutions are roughly determinable, and these are the features upon which we can rely in oceanic tropical analysis. With sparse data, of course, we can only generalize about the true field which the observations have sampled. Nevertheless, we can say something.

Figure 9 shows a series of analyses of the 500-mb surface over the southern North Pacific; these maps are copied without alteration from the Northern Hemisphere Maps [U. S. WEATHER BUREAU, 1950] for the period March 15-30, 1949. A study of the maps shows that on March 15 a cyclonic circulation can be drawn at 500 mb between Wake Island and Kwajalein, that this circulation disappeared on March 16, that a similar circulation existed between Johnston Island and the Hawaiian Islands on March 21, and that after March 21 the latter circulation is quasi-stationary in the Hawaiian area.

We now apply the hypothesis of the previous section to these maps. Figures 10 to 14 represent a re-analysis of all the available data for the period March 15-19, 1949. The details of the contours differ from those of the Northern Hemisphere Maps and it is impossible to decide whether

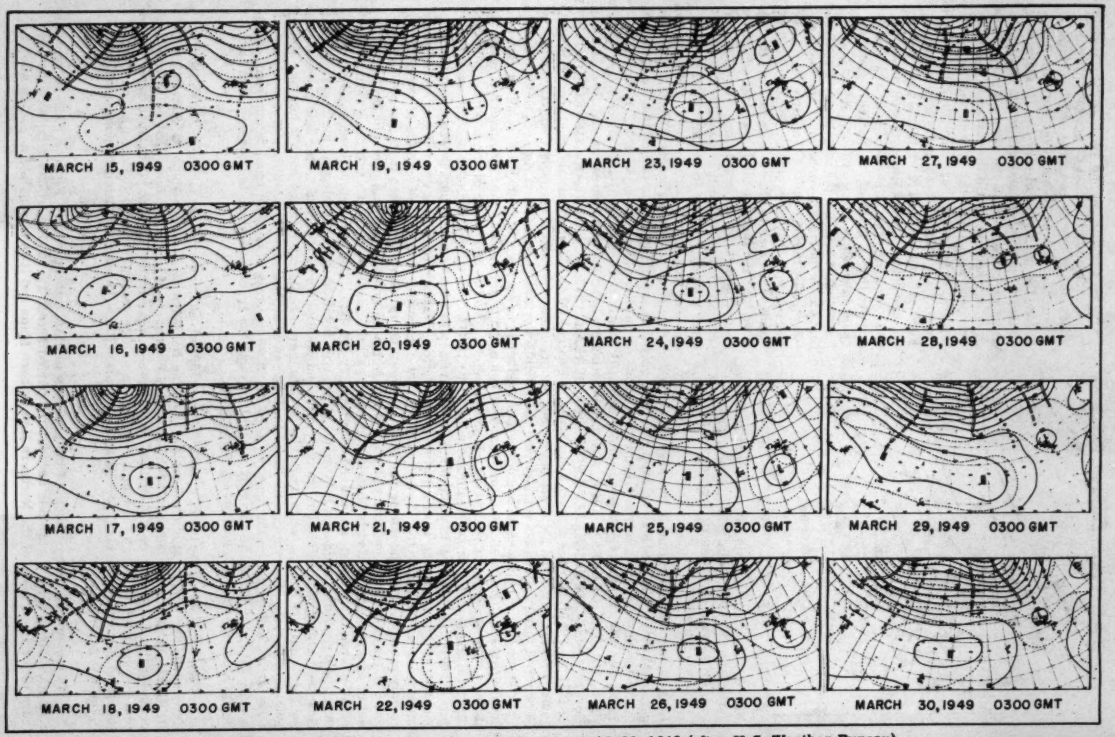


Fig. 9--Southern North Pacific, 500-mb contours, March 15-30, 1949 (after U.S. Weather Bureau)

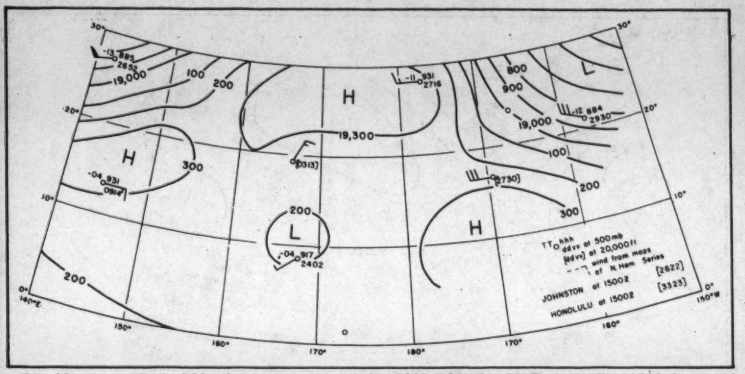


Fig. 10--Re-analysis 500-mb contours, March 15, 1949, 03h 00m GMT; solid lines, 100-ft contours; arrows, wind direction with barbs showing speed in knots; one long barb = 10 knots

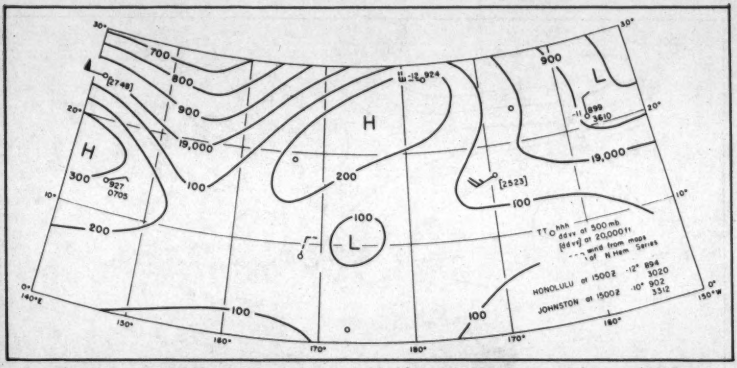


Fig. 11--Re-analysis 500-mb contours, March 16, 1949, 03h 00m GMT; solid lines, 100-ft contours; arrows, wind direction with barbs showing speed in knots; one long barb = 10 knots

one or the other set of analyses, or neither, is correct in these details. It is possible, however, to deduce certain features which are common to the analyses presented here and those of the Northern Hemisphere Maps, and a close inspection of the data will show that these features are impressed upon both, or any, analyses, by the hard facts of observation. These features are:

(a) On March 15, 1949 a cyclonic circulation existed at 500 mb over the Marshall Islands. The data show that this circulation was present at all layers between 10,000 and 20,000 ft (as high as the Wake Island data extend).

(b) On March 16 the circulation can no longer be found in the Marshall Islands. Several hypotheses might be suggested.

(1) The cyclone disappeared spontaneously at all levels. This cannot be disproved, but is contrary to experience in higher latitudes.

(2) The cyclone moved toward the west. This is contradicted by subsequent observations up to March 31. There is no sign of such a disturbance in the west, either at Guam or in the Philippines. Moreover, from March 18 the height of the 500-mb surface consistently rose west of and, later, over the Marshall Islands.

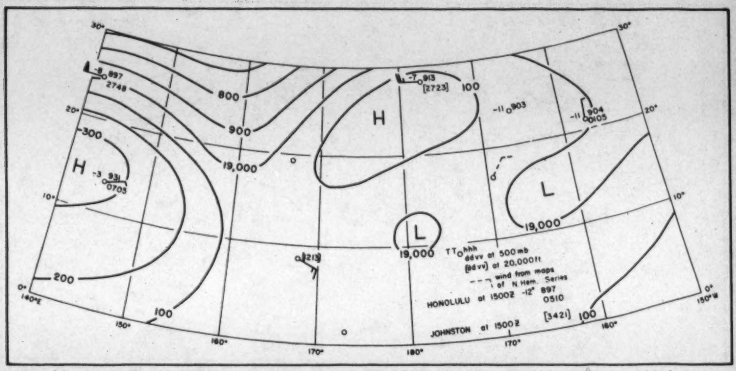


Fig. 12--Re-analysis 500-mb contours, March 17, 1949, 03h 00m GMT; solid lines, 100-ft contours; arrows, wind direction with barbs showing speed in knots; one long barb = 10 knots

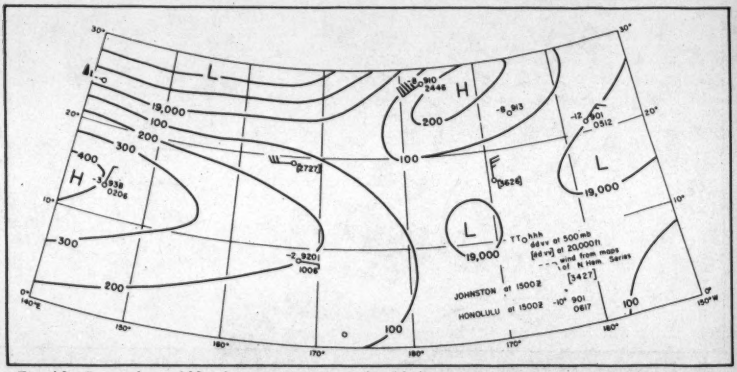


Fig. 13--Re-analysis 500-mb contours, March 18, 1949, 03h 00m GMT; solid lines, 100-ft contours; arrows, wind direction with barbs showing speed in knots; one long barb = 10 knots

(3) The cyclone moved southward. This cannot be rejected outright. Great movement southward is, however, repugnant to our ideas concerning cyclones situated near the equator and is contrary to our experience with well-formed vortices at lower levels.

(4) The cyclone moved northward. On March 16 and 17 there is considerable evidence for the persistence of high values of the 500-mb contours north and northeastward of the Marshalls. This hypothesis must be rejected.

(5) The cyclone moved eastward. This is consistent with wind changes from 20,000 ft upward at Johnston Island on March 18 and at Honolulu on March 19-22.

The two most probable hypotheses in the above list are (1) and (5). If we accept (1) we have to conclude that there were two cyclones, one over the Marshalls on March 15 that disappeared spontaneously on March 16 and another that appeared spontaneously on March 20 between Johnston Island and the Hawaiian Islands. The principle of simplicity requires us to regard this hypothesis as less probable than (5). We may allow a southerly component to the movement of the cyclone on March 16 and perhaps March 17, thus combining hypotheses (3) and (5) but after March 17 the dis-

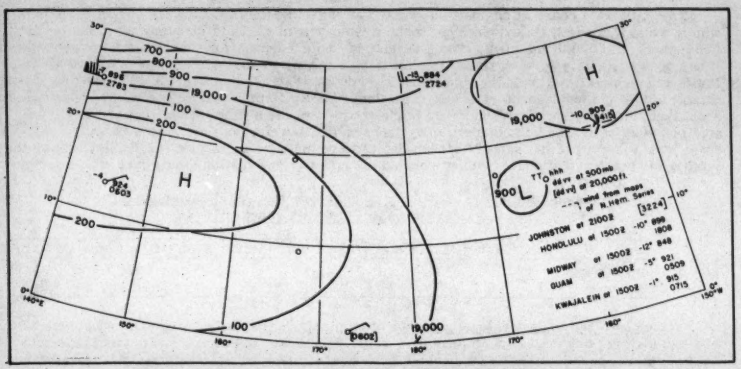


Fig. 14--Re-analysis 500-mb contours, March 19, 1949, 03h 00m GMT; solid lines, 100-ft contours; arrows, wind direction with barbs showing speed in knots; one long barb = 10 knots

turbance must move eastward and, as a compensation for any previous southward excursion, northward.

Other features, of course, confirm hypothesis (5). Figure 9 shows that the type of analysis displayed on Figure 10 was still applicable many days later and that a great simplification would be brought to the relevant Northern Hemisphere maps in the tropical North Pacific area by the introduction of the cyclone over the Marshalls on March 15, its movement toward the Hawaiian Islands at 17 knots from March 16-20, by holding it quasi-stationary in the Hawaiian area from March 21-27, and by its subsequent movement into higher latitudes between the Hawaiian group and the west coast of North America. From March 21 to 23 the low had the characteristics usually ascribed to the early stages in the development of a "kona" storm. Reference to the Northern Hemisphere Maps after March 30 will also show that a continuation of the analytic hypothesis suggested here would introduce a continuing simplification up to April 14. The simplification would involve the passage of the low on to the west coast of North America during April 3-7 and finally its passage across the southern United States from April 7 to 14.

The frequency of upper-level Hawaiian cyclones--There would be little importance in the detailed considerations we have just pursued if they were concerned with rare anomalies of the upper tropospheric circulation in the tropics. I have therefore made a rough survey of such 500-mb maps of the Historical Series for 1949 as were available in order to determine, first, on how many days the circulation in the vicinity of the Hawaiian group appeared to be dominated by cold lows at and below this surface, secondly, the total number of individual storms, irrespective of their duration, in the area, and thirdly, the number of circulations that, from the observations displayed in the Series, might plausibly be considered to have originated in the manner described in this paper. The results are shown in Table 1.

Table 1--Estimates of frequency of cold lows of tropical origin in 1949

Item	Jan.	Feb.	Mar.	Apr.	May	July	Aug.	Sept.	Oct.	Nov.	Total
Total number of days with cold low in Hawaiian area	27	12	16	12	4	14	17	12	13	7	134
Number of separate cold lows originating during month	2	1	1	1	2	1	2	2	1	2	15
Number of cold lows of tropical origin	1	1	1	1?	1	1	...	2	1	1?	8?

January 1949 was a remarkable month. During most of the period the tropical atmosphere west of the Hawaiian group was controlled by a "kona" storm, which, originating at high levels, worked gradually down to the surface and remained quasi-stationary throughout January and part of February. High winds and much rain were experienced in various parts of the Hawaiian group during the sway of this storm.

The California coast--Considerable rains may fall in Southern California during periods in which, while there is little evidence of frontal systems or of cyclonic circulations in the lower atmosphere, at 500 mb and above a well-developed "cold" depression moves slowly over the area. It has been customary to analyze the maps in such a way as to attribute a polar origin to all these Californian upper-level cyclones, and there is no doubt whatever that some of the lows are of polar origin, following the sequence of development described by Palmén very closely. There is also no doubt that some of the cyclones move on to the coast from the southwest and that some of these may plausibly be traced back to similar cyclones in the Hawaiian region. Table 2, which is derived from a survey of the same Northern Hemisphere maps as were used for Table 1, shows the number of cyclones that could, without contradiction to the observations, have had such an origin.

Table 2--Estimates of number of cold lows that could have moved from Hawaiian region to California coast in 1949

Item	Jan.	Feb.	Mar.	Apr.	May	July	Aug.	Sept.	Oct.	Nov.	Total
Cold lows moving during month	1	2	...	1	1	1	1	1	1	...	9

Problems raised by upper-level cyclones of tropical origin--If the foregoing hypotheses are substantiated, not only will certain problems which were latent in Palmén's researches become acute but other, peculiarly analytic, problems in tropical meteorology will have to be considered. The following is a brief summary of the questions which will be matters for future research.

(a) Problems of analysis--Workers on the Tropical Project have found that 20,000 ft is frequently the lowest level at which an upper-level cyclonic singularity of the type we are considering may be found in the regions south of 15° N. This is very close to the 500-mb surface. Slight errors in computing the height to which pressure, temperature, and wind observations must be referred can, therefore, make a considerable difference in the type of analytic model applied to the 500-mb contour analysis. Thus, on a certain synoptic map, a cyclonic circulation may be found on the surface, but some hours later no trace of the circulation can be seen. Not until the analysis ascends to a slightly higher level does the circulation again become apparent. If only the 500-mb surface is analyzed, then, it may happen that the cyclone appears and disappears on this one surface in a very erratic manner, while an analysis at 400 mb gives good continuity. This we have attributed to the fact that in such cases 500 mb is very close to the lowest level at which the disturbance possesses a singularity and the erratic behavior at this surface is due to the erratic distribution of the height computational errors. But, of course, it is also possible that the disturbance itself "pumps" up and down slightly through the surface. To make a fetish of continuity in the analysis of the surface would then lead to obvious absurdities.

We are accustomed to applying a synoptic model in which we have a change from closed low to open wave as we proceed aloft. The work here described warns us that we must also consider the continuity problems that arise when we have a closed low aloft superimposed upon an open wave below. In the former case we have been accustomed to exploring the surface cyclone thoroughly by analysis and feel satisfied that we can explain in terms of air-mass dynamics the relation of the open wave aloft to the cyclone below. But here we are confronted with the opposite problems, namely, explaining the open wave below, apparently a quasi-stationary disturbance in an autobarotropic current, by its relation to an active and frequently an intensifying cyclone aloft. It is clear that these problems can be attacked only if we have many more observations at higher and higher levels. Perhaps the events at 20,000 ft become explicable only in terms of events in the highest part of the tropical troposphere, or perhaps the stratosphere.

(b) The problem of origin--Palmén's explanation of the origin of upper-level cyclones in middle latitudes has been accepted almost without question. It is, essentially, an explanation in terms of advection of cold air, strictly in conformity with classical air-mass theory. An air-mass theory is obviously inadequate to deal with the events of June 1946 over the Marshall Islands. By no stretch of the imagination can a polar air mass be brought down from far northern latitudes, keeping its temperature below that of its surroundings at all times, to rotate above 30,000 ft over the Marshall Islands. Even if we could postulate such a process, we would then have to explain why the circulation began to increase and reach lower levels from June 9 onward, which is precisely the problem of origin. After working with the data of these circulations for some time one is irresistibly drawn toward the conviction that the sufficient causes for the initiation and intensification of the cyclones must be sought at levels exceeding those routinely observed by weather services, and in dynamic processes not directly dependent on a balance among the pressure, Corolis', and centrifugal forces.

(c) The problem of maintenance--The manner in which upper-level cyclones, both of polar and tropical origin, are maintained for many days, largely independent of the surface air-mass distribution, is also an acute problem. For, while the frictional dissipation of kinetic energy within the circulation must be small at the high levels where it is usually found, the long period during which the cyclone remains stationary in low latitudes more than offsets the small rate of energy loss. Quite apart from the problem of the intensification of the cyclone, then, is the problem of the source of the kinetic energy required to maintain the storm. Palmén [1949] was not explicit on this point when it arose in connection with the cold lows of polar origin, but it is clear that the dynamical explanation which his work implies cannot apply to upper-level cyclones that are stationary in very low latitudes.

As always in geophysics, it is not difficult to speculate about causes nor to suggest hypotheses; the difficulty is to order the suggested causes according to the magnitude of the effects they would produce.

(d) The problem of movement--The high-level cyclones of the Hawaiian region have presented interesting and important practical problems in forecasting in the field. Once the establishment of the storm and the fact that it is quasi-stationary have been recognized, the forecaster is in an enviable position. He may use extrapolation of present conditions with marked success, provided he makes allowances for the passage of minor disturbances in the lower atmosphere and for minor changes in position of the upper-level circulation. This type of forecasting may be very successful for periods of over a week. Sooner or later, however, the forecaster becomes anxious about the possibility of rapid movement out of the area. Since the movement begins suddenly, an important problem is that of finding premonitory synoptic signs, or dynamic explanations, of the sudden transition from the quasi-stationary to the moving state.

Here we may offer promising suggestions. The situations so far examined by workers on the Tropical Project strongly suggest that the upper-level cyclone remains stationary for as long as the upper-level waves in the westerlies have a small amplitude, which in advective terms, means as long as there is no large influx of relatively cold air from high latitudes south of the belt of maximum westerlies. As soon as a large influx takes place, as indicated by a rapid extension of the cold trough pertaining to a wave southward and southeastward at the appropriate levels, the formerly stationary cyclone begins to move. The situations presented in this paper suggest this development strongly; some of the Northern Hemisphere analyses are even more open to this interpretation.

Acknowledgments--I am indebted to G. Dean, O. Stopinski, Captain, USAF, and F. Miller, Lieutenant, USAF, of the Tropical Project, for analyses of the June 1946 situation, and to Theodore B. Smith of the American Institute of Aerological Research for valuable data from March 1949. The work described in this paper has been made possible through support and sponsorship extended by the Air Force Cambridge Research Laboratories, Air Materiel Command, U. S. Air Force, under contract No. W28-099ac-385. It does not represent recommendations or conclusions of the sponsoring agency.

References

BJERKNES, V., and Others, Dynamic meteorology and hydrology, pt. 2, kinematics, Carnegie Institution of Washington, 1911.

COMMANDER, JOINT TASK FORCE ONE, Aerological report on operation crossroads, OPNAV-JTF-P1001, Washington, 1947.

COMMONWEALTH WEATHER BUREAU, AUSTRALIA, Selected Australian weather reports: 14th March to 30th March 1949, Weather Bureau, Melbourne, 1949.

CROCKER, A. M., W. L. GODSON, and C. M. PENNER, Frontal contour charts, J. Met., v. 4, pp. 95-99, 1947.

DEAN, G. A., The weather situation in the Marshall Islands on the 9th, 10th and 11th June 1946, pt. 3, the upper atmosphere, Ap. A, 11th Quarterly Rep. Tropical Project, Geophys. Res. Dir., Cambridge Field Station, USAF, 1951.

DEAN, G. A., F. MILLER, and O. STOPINSKI, The weather situation in the Marshall Islands on 17th, 18th, and 19th June 1946, Ap. A, 12th Quarterly Rep. Tropical Project, Geophys. Res. Dir., Cambridge Field Station, USAF, 1951.

HEADQUARTERS, AIR WEATHER SERVICE, Northern Hemisphere historical weather maps, June 1946, Washington, Air Weather Service, AAF, 1948.

LANDERS, H., The weather situation in the Marshall Islands on the 9th, 10th, and 11th June 1946, pt. 2, orders of magnitude of certain atmospheric parameters, Ap. A, 10th Quarterly Rep. Tropical Project, Geophys. Res. Dir., Cambridge Field Station, USAF, 1950.

NEW ZEALAND METEOROLOGICAL SERVICE, Daily weather bulletin, Pacific Islands Section, March 1949, Meteorological Office, Wellington, 1949.

PALMÉN, E., Origin and structure of high-level cyclones south of the maximum westerlies, Tellus, v. 1, pp. 23-31, 1949.

PALMER, C. E., and G. A. DEAN, The weather situation in the Marshall Islands on the 9th, 10th, and 11th June 1946, pt. 1, the lower atmosphere, Ap. A, 9th Quarterly Rep. Tropical Project, Geophys. Res. Dir., Cambridge Field Station, USAF, 1950.

SANDSTROM, O. W., Ueber die Bewegung der Flussigkeiten, An. d. Hydrographie und Maritimen Met., pp. 242-254, June 1909.

SCHWERDTFEGER, W., Untersuchungen über den Aufbau von Fronten und Kaltlufttropfen, Ber. d. Deut. Wetterdienstes, U.S. Zone, no. 3, 1948.

U. S. WEATHER BUREAU, Daily upper-air bulletin, March 14-20, 1949, U. S. Weather Bureau, Washington, 1949.

U. S. WEATHER BUREAU, Daily series synoptic weather maps, March 1949, U. S. Weather Bureau, Washington, 1950.

Institute of Geophysics,
University of California,
Los Angeles, California

(Manuscript received March 5, 1951; presented at the Twenty-Sixth Meeting, Fresno, California, February 9, 1951; open for formal discussion until March 1, 1952.)

Transactions, American Geophysical Union Volume 32, Number 5 October 1951

FREE FALL OF DROPS THROUGH AIR

Walter Hitschfeld

Abstract--Terminal velocity data of water drops are used for the quantitative description of their accelerated motion when falling freely from rest. The method, based on the principle of aerodynamic similarity, is valid for water drops of radius 1.6 mm or less.

Using, as an example, the Schmidt relation for terminal velocity, general expressions are obtained for the time of fall and the distance fallen as functions of the velocity of fall attained. Numerical results calculated for drop radii of 0.625, 1.00, and 1.50 mm agree well with the measurements of Laws.

Introduction--In connection with an experiment performed by GUNN and HITSCHFELD [1951], as well as in other laboratory studies of the behavior of falling drops, the variation of the particle velocity with time or distance has to be known. This variation of the velocity v while the drop is accelerating has not been studied very extensively, while many experimenters have measured the terminal velocity v_T of water drops in air [see LENARD, 1904; SCHMIDT, 1909; LAWS, 1941; SMITH, 1944; GUNN and KINZER, 1949]. Analytical expressions for the terminal velocity in terms of the particle density and size and the environmental conditions have also been given with varying degrees of success [see SCHMIDT, 1909, and BEST, 1950, for raindrops in air].

It is the purpose of this paper to set up the equations of motion of a drop accelerating freely under a constant force, and to describe a simple method for solving these equations, provided the relation of v_T to the drop radius r is known, either numerically or analytically.

Theory--A freely falling particle of mass m is subject to the force of gravity (= g m), and to the drag force D. The resulting acceleration is thus a = g - D/m. The equations of motion of such a particle can then be written in the form

$$dv/dt = v\, dv/ds = g - D/m \quad \ldots\ldots (1)$$

where v is the particle speed, s is the displacement, and t is the time. The solutions of these equations are

$$t = \int_0^v dv/(g - D/m) \quad \text{and} \quad s = \int_0^v v\, dv/(g - D/m) \quad \ldots\ldots (2)$$

For the evaluation of the integrals, D must be known in terms of v.

Consider a particle A of radius r_A falling at its terminal velocity v_{AT}, thus having a terminal Reynolds number

$$R_{AT} = 2\, r_A\, v_{AT}/\nu \quad \ldots\ldots (3)$$

where $\nu = \eta/\rho$ is the kinematic viscosity, η the absolute viscosity, and ρ the density of the medium.

When this particle falls at its terminal velocity, the drag force D_{AT} equals the particle weight

$$D_{AT} = (4/3)\, \pi r_A^3\, \rho' g \quad \ldots\ldots (4)$$

ρ' being the particle density. This force can also be written in a form involving the drag coefficient C_{AT} of the particle

$$D_{AT} = (1/2)\, \rho v_{AT}^2\, \pi r_A^2\, C_{AT} = (\pi/8)\, \rho \nu^2\, R_{AT}^2\, C_{AT} \quad \ldots\ldots (5)$$

Since the drag coefficient is itself a function of the Reynolds number only, it follows that, apart from ρ and ν (properties of the medium), D_{AT} depends only on the appropriate Reynolds number R_{AT}.

Consider now the particle X of radius r ($> r_A$) whose accelerated motion is under study. At any instant when its velocity is v, its Reynolds number is $R = 2rv/\nu$. If now r_A is so chosen that

$$R = R_{AT} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

then the drag force D on particle X equals the terminal drag force D_{AT} on particle A, that is

$$D = D_{AT} = (4/3)\,\pi\rho' g\, r_A^3 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

The solutions of (2) can now be written in the form

$$t = (r^3/g)\int_0^v dv/(r^3 - r_A^3) \quad \text{and} \quad s = (r^3/g)\int_0^v v\, dv/(r^3 - r_A^3) \quad \ldots\ldots\ldots\ldots (8)$$

These forms are more convenient than (2) because r_A can be evaluated for any value of v by first calculating R, and then finding the drop radius r_A whose terminal Reynolds number equals R. This can always be done if tables or curves giving $v_T(r)$ are available. If $v_T(r)$ is available in a suitable analytical form, it may be possible to substitute directly for r_A^3, and to render (8) integrable.

Discussion--In the above argument it was assumed that the principle of aerodynamic similarity is applicable; thus the drag coefficient C at any velocity was treated as a function of R only. This assumption is perfectly valid for spheres in equilibrium motion [see GOLDSTEIN, 1938, or SCHILLER, 1932]. Liquid drops, on the other hand, deviate more or less from the spherical shape, and we are not dealing with equilibrium motion.

The extent of the particle deformation depends on the properties of the liquid and the medium. For drops falling at terminal velocities, but at low Reynolds numbers under the influence of gravity, BOND and NEWTON [1928] have suggested an equation

$$r_0 = \sqrt{\gamma/(|\rho - \rho'|g)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

from which the order of magnitude r_0 of the value of r at which the deformation becomes serious can be found. (Here, γ is the surface tension at the surface of the drop.)

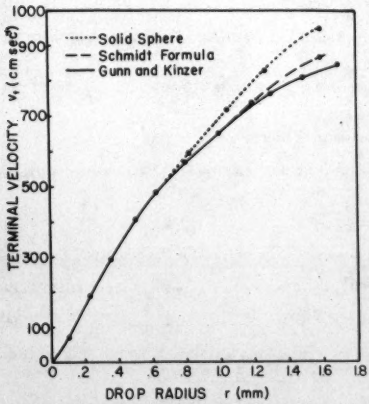


Fig. 1--Terminal velocity of fall through air at 20° C and 760 mm pressure of waterdrops according to the measurements of GUNN and KINZER [1949]; waterdrops according to the Schmidt formula (10); and solid spheres of unit density

In the case of water drops falling through air at 20° C and 760 mm pressure, the effect of the deformation can be seen from Figure 1, where the terminal speeds of water drops, measured by GUNN and KINZER [1949], and of solid spheres of unit density, calculated from the values of C(R) given by GOLDSTEIN [1938], are plotted. The difference between these speeds increases with the radius, reaching about five per cent at r = 1.0 mm and 12 pct at 1.6 mm. This is probably mainly because of change in shape, as has been suggested by LAWS [1941] and SPILHAUS [1948].

The effect of the acceleration (and possibly of higher time derivatives) on the drag coefficient has not been studied in any detail. SCHMIDT [1920] and LUNNON [1926, 1928] have made some measurements of this effect, but not in the range of R with which we are concerned. Qualitative reasoning would suggest that the presence of acceleration tends to increase the drag force, so that the speed of the drops will be somewhat less than that calculated by disregarding the acceleration [SCHILLER, 1932]. This effect, though probably nowhere large, would be a maximum in the early stages of the motion.

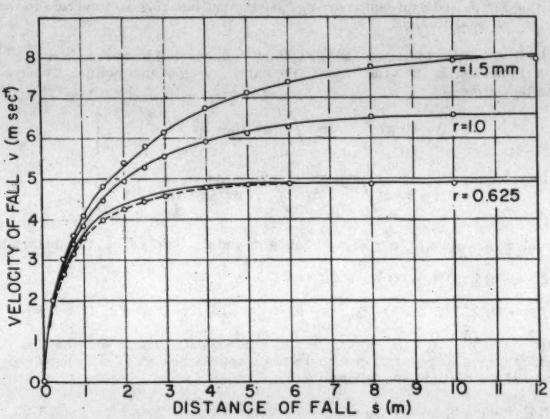


Fig. 2--Velocity of free fall of waterdrops through air at 20°C and 760 mm pressure; solid line calculated from the theory including the Schmidt formula (14); dashed line calculated from the theory without Schmidt formula, by direct integration of (8) on the basis of the data of GUNN and KINZER [1949]; the circles indicate the corresponding measurements of LAWS [1941]

The method under discussion is thus completely satisfactory for solid spheres and for small liquid drops. In the case of water drops falling through air, very good approximations can be obtained for radii 1.3 mm or smaller, the error introduced being much smaller than may be suggested by the above comments on Figure 1 (see Fig. 2). Beyond 1.6 mm, however, the error caused by the simplification in the theory becomes increasingly serious.

Application to the Schmidt formula--SCHMIDT [1909] has suggested a simple semi-empirical formula for terminal velocities of spheres and drops which reduces to Stokes' relation for small radii and Newton's relation ($v_T \propto r^{0.5}$ for large ones. In the form discussed by FRÖSSLING [1937] this formula is

$$v_T = 2\rho' g r^2/[9\eta + (1.5\ \rho\rho' g C')^{0.5} r^{1.5}] = a r^2/(b + c r^{1.5}) \quad \ldots\ldots\ldots (10)$$

where C' (= 0.45) is the value of the drag coefficient of spheres corresponding to large sub-critical Reynolds numbers. Values of v_T calculated according to (10) for water drops in air at 20° C and 760 mm pressure, $a = 10^6$, $b = 0.830$, and $c = 454$, are shown in Figure 1, indicating that this formula compares well (within about two per cent) with measurement for r less than about 1.6 mm.

Using (10) it is possible to replace r_A in (8) by a function of the parameters a, b, c, and of v and r; the integrals of (8) can then be evaluated analytically.

Since r_A is the radius of a drop whose terminal Reynolds number is equal to that of the particle of radius r when moving at velocity v, it follows that $v_{TA} = vr/r_A$ which combined with (10) leads to

$$r_A^3 = \left\{2c^2 (rv)^2 + 4ab (rv) + 2c (rv) [c^2 (rv)^2 + 4ab (rv)]^{0.5}\right\}(1/4a^2) \quad \ldots\ldots\ldots (11)$$

The product rv, being related to the Reynolds number, may be denoted by R'. Expression (11) can be simplified for large values of R' (say $R' > R'_0$) by expanding the square root and retaining only the first three terms

$$2cR' (c^2R'^2 + 4ab\ R')^{0.5} \doteq 2c^2R'^2 [1 + 2ab/c^2\ R' - 2a^2b^2/c^4\ R'^2] \quad \ldots\ldots\ldots (12)$$

If the resulting simplified expression for r_A^3 is then put into (8), the integrals in that equation can be worked out analytically.

When R′ is small, on the other hand, r_A^3 may be neglected in comparison to r^3 in (8). This is equivalent to neglecting the drag force in the early stages of the motion. These equations appear then in the forms

$$\left.\begin{aligned} t &= (1/g)\int_0^{v_0} dv + \int_{v_0}^{v} dv/(A + Bv + Cv^2) \\ s &= (1/g)\int_0^{v_0} v\,dv + \int_{v_0}^{v} v\,dv/(A + Bv + Cv^2) \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots (13)$$

where $v_0 = R_0'/r$, $A = g(1 + b^2/c^2r^3)$, $B = -2gb/ar^2$, and $C = -gc^2/a^2r$. The integrations result in

$$\left.\begin{aligned} t &= v_0/g + (1/q)\log_e [(v + \alpha)(v_0 + \beta)/(v + \beta)(v_0 + \alpha)] \\ s &= v_0^2/2g + (1/2C)[(1 - B/q)\log_e (v + \alpha)/(v_0 + \alpha) + (1 + B/q)\log_e (v + \beta)/(v_0 + \beta)] \end{aligned}\right\}. \quad (14)$$

where $q = (B^2 - 4AC)^{0.5}$, $\alpha = (B - q)/2C$, and $\beta = (B + q)/2C$. These solutions for t and s tend to infinity (as they should on physical grounds) when v approaches $v' = -\beta$, where $v' \doteqdot v_T$, the terminal velocity of the particle according to (10).

Using (14), values of s were calculated for water drops of radius r = 1.50, 1.00, and 0.625 mm falling through air at 20° C and 760 mm pressure. The results are shown in Figure 2 where the measurements of LAWS [1941] are also shown for comparison. The agreement between calculated and observed values is seen to be very good for the larger drops, but the computed values of s are somewhat high for r = 0.625 mm because the above approximation that $r_A^3 \ll r^3$ when $v < v_0$ is not very good here. For this reason, values of s corresponding to this smallest drop size have also been obtained without using the Schmidt equation by a direct graphical integration of (8) using the data of GUNN and KINZER [1949]. These are shown in Figure 2 in the dashed line.

References

BEST, A. C., Empirical formulae for the terminal velocity of drops falling through the atmosphere, Q. J. R. Met. Soc., v. 76, pp. 302-311, 1950.

BOND, W. N., and D. A. NEWTON, Bubbles, drops, and Stokes' law, Phil. Mag., v. 5, pp. 794-800, 1928.

FRÖSSLING, N., Über die konstante Fallgeschwindigkeit von Kugeln, Ger. Beit. Geophysik, v. 51, pp. 167-170, 1937.

GOLDSTEIN, S. (ed.), Modern developments in fluid dynamics, Oxford Univ. Press, v. I, p. 16; v. II, pp. 491-528, 1938.

GUNN, K., and W. HITSCHFELD, A laboratory investigation of the coalescence between large and small water-drops, J. Met., v. 8, pp. 7-16, 1951.

GUNN, R., and G. D. KINZER, The terminal velocity of fall for water droplets in stagnant air, J. Met., v. 6, pp. 243-248, 1949.

LAWS, J. O., Measurements of the fall velocity of water-drops and raindrops, Trans. Amer. Geophys. Union, v. 22, pp. 709-721, 1941.

LENARD, P., Über Regen, Met. Zs., v. 21, pp. 248-262, 1904.

LUNNON, R. G., Fluid resistance to moving spheres, Proc. R. Soc. (A), v. 110, pp. 302-326, 1926, and v. 118, pp. 680-694, 1928.

SCHILLER, L., Fallversuche mit Kugeln und Scheiben, Handbuch der Experimentalphysik, Wien-Harms, pt. 4, v. 2, pp. 339-387, 1932.

SCHMIDT, F. S., Zur beschleunigten Bewegung kugelförmiger Körper in widerstehenden Mitteln, Ann. Phys., v. 61, pp. 633-664, 1920.

SCHMIDT, W., Eine unmittelbare Bestimmung der Fallgeschwindigkeit von Regentropfen, SitzBer. Wiener Akad. Wiss., v. 118, No. 2a, pp. 71-84, 1909.

SMITH, E. D., Notes on raindrop sizes and attenuation of one-way microwave radio transmission, Third Conference on Propagation, Washington, D. C., 16 Nov. 1944.

SPILHAUS, A. F., Raindrop size, shape, and falling speed, J. Met., v. 5, pp. 108-110, 1948.

Department of Physics,
McGill University,
Montreal, Quebec, Canada

(Manuscript received April 10, 1951; presented at the Thirty-Second Annual Meeting, Washington, D. C., May 1, 1951; open for formal discussion until March 1, 1952.)

ON SUMMERTIME RAINFALL AT NEW YORK, N. Y.

David K. Todd

Abstract--Data are presented showing the diurnal variation of precipitation frequency for the months of June, July, and August at New York, N. Y. Suggestions are made as to the probable causes of the three periods of maximum frequency found to exist and coincide chronologically in each of the three monthly curves.

Introduction--In these days of man-modified rainfall, the natural conditions most conducive to rainfall become of considerable importance. This study is concerned with summertime rainfall conditions, primarily thunderstorm activity, at New York, N. Y. Fifty years of hourly precipitation records were tabulated to determine the frequency of precipitation for each hour of the day during the summer months. The resulting monthly diurnal frequency curves all exhibit the same general form to a surprising degree, indicating the similarity of conditions from month to month.

Previous studies of diurnal variation of precipitation for the United States have been made by several investigators [LONG, 1928; COUNTS, 1933; ALEXANDER, 1938; COOK, 1939; MARTIN, 1942], while other studies have been made in connection with comprehensive climatological summaries for cities. Examples of such studies are those by COX and ARMINGTON [1914] for Chicago, FASSIG [1907] for Baltimore, and U. S. WEATHER BUREAU [1949] for Washington, D. C. GREELEY [1888] computed the diurnal variation of precipitation for New York City based on only seven years of record, which proved to be too short a period for eliminating random variations in the precipitation pattern.

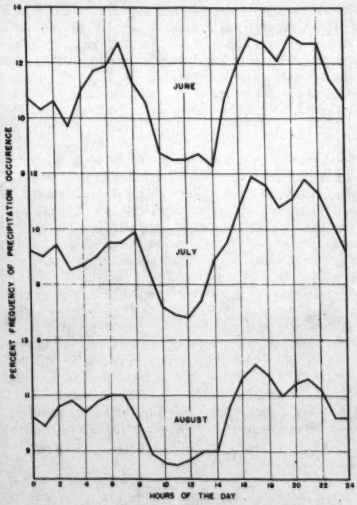


Fig. 1--Diurnal variation of precipitation frequency for three summer months at New York, N. Y. (hour ending at the time indicated)

Data--Precipitation records for the 50-year period 1898-1947 of the New York Meteorological Observatory, Central Park, New York [U. S. WEATHER BUREAU, 1898-1947] were employed. Precipitation occurrences for each hour of the day for each of the months, June, July, and August, were tabulated. A trace or more of rainfall was counted as a precipitation occurrence for the purposes of this study. Rainfall frequencies were computed as percentages of the number of occurrences of rainfall in a given hour to the total number of such hours in the 50-year period. Individual hourly frequencies plotted as curves of diurnal variation of rainfall occurrences are shown in Figure 1 for the three summer months. Hourly values refer to precipitation in the hour just ending; thus the percentage for 16h 00m includes the hour from 15h 00m to 16h 00m. All data are based on EST.

Comparison of monthly curves--It can be noted that the three monthly curves of Figure 1 exhibit very similar shapes. This indicates, first, that the period of record was of sufficient length to eliminate short-period variations and to reveal the long-time average daily rainfall distribution; and, second, that similar meteorological conditions influence the rainfall during each of these summer months.

The outstanding features of the frequency curves are the early morning maximum at 07h 00m, the midday minimum, and the double maximum in the late afternoon and evening

hours, occurring near 17h 00m and 21h 00m. It should be remembered that curves of this type represent only the average long-time distribution, but as such they are indicative of certain continually predominant conditions favorable to rainfall. In summer about 60 pct of all rainfall at New York can be traced to thunderstorm activity and more than 80 pct of all rainfall occurs in the second half of the day [U. S. WEATHER BUREAU, 1898-1947]; hence the diurnal fluctuations of meteorological elements become the controlling factors in the time of precipitation. The subject of thunderstorms and the release of convective rainfall is one of great complexity. Nevertheless, the common pattern found in each of the diurnal precipitation curves implies that certain key factors or conditions recur continually to cause the same precipitation pattern to persist throughout the summer months. Of particular interest are the phenomena in conjunction with the three periods of maximum precipitation frequency.

Analysis of maxima--The morning maximum, situated between 06h 00m and 08h 00m, occurs roughly two hours after sunrise. Because the number of precipitation occurrences builds up gradually in the hours immediately preceding this maximum, most favorable conditions must exist near and shortly after sunrise. This gradual increase during the late night hours until after sunrise may be attributed to instability resulting from radiational cooling of the atmosphere.

This phenomenon accounts for the nocturnal maximum of instability and thunderstorms over oceans [PETTERSSEN, 1940, p. 98]. Accordingly, this maritime influence may be expected at coastal stations. The diurnal variation of precipitation frequency by weeks at Washington, D. C. [U. S. WEATHER BUREAU, 1949] also shows a morning maximum. Shortly after sunrise more stable conditions develop because of the uniformity of temperature induced in the lowest layers of the atmosphere by the adjacent ocean areas; thus a sharp decline in the precipitation frequency follows. It has been suggested [U. S. WEATHER BUREAU, 1947, p. 212] that a morning maximum might be caused by a land-breeze cold front. This suggestion would have to be based on forced lifting at the cold front and not on instability showers, since cold air underlying warm air is by itself a stable condition. Early morning heating over land would tend to destroy the temperature differential causing the front, and precipitation would then decrease. However, because land breezes are restricted to a shallow layer of the atmosphere and are usually quite weak, it seems doubtful that land-breeze cold fronts could be very important in causing early morning rainfall.

The double maximum occurring in the late afternoon and evening hours appears to be significant because of its presence on all three of the monthly curves and its chronological agreement. This phenomenon has not been noted by previous investigators and of course brings up the question whether this double maximum is peculiar to New York or whether studies at other localities have failed to detect it because of insufficient lengths of records. The Washington, D. C. study [U. S. WEATHER BUREAU, 1949], which provides the most complete study in this general area to date, indicates only a single maximum based on 57 years of record. This point will be of interest in future studies of the subject.

The maximum at 17h 00m may be attributed to thunderstorms resulting from insolational heating in the afternoon hours. The lag of approximately two hours from the time of maximum surface heating to the time of maximum frequency of occurrence may be explained as the time required for a thunderstorm to develop to its greatest intensity. A partial verification of this is provided in the very comprehensive study of thunderstorms by BYERS [1949]. He studied the diurnal variation of the development of convective clouds causing radar echoes, based on a 17-day period in Florida. The time of maximum initial convective cloud echoes was near 13h 00m, indicating, at least for that short period, that clouds form early in the day and maximum precipitation frequency is reached several hours later. The effect of the sea breeze in one way or another may also be important in this problem of the time of maximum thunderstorm development. The sea breeze tends to limit surface heating at coastal stations, which in turn tends to delay thunderstorm development until later in the afternoon. Thus, at New York, storms have either developed inland earlier in the afternoon and have moved into the area, or the retarding influence of the sea breeze has been overcome by 17h 00m. Another possible effect of the sea breeze is indicated in a recent study by BYERS and RODEBUSH [1948], who measured the diurnal variation of convergence due to the sea breeze on the Florida peninsula and along the Gulf Coast and found a period of maximum convergence in the lower 2000 ft of the atmosphere in both areas at 17h 00m. Although this maximum cannot be presumed to exist at New York until verified there, it is interesting because of its chronologic coincidence with the frequency maximum at New York.

The second half of the double maximum, occurring near 21h 00m, has no obvious physical explanation. The hypothesis of instability developing from radiational cooling of cloud tops is inadequate. This process would favor more precipitation later rather than earlier at night. Also, DEXTER [1944] has computed this cooling effect to amount to only 0.5° C per km per 12 hr, which

indicates its contribution to instability is small. Normally there is a large amount of convective cumulus remaining in the sky immediately after sunset, but the impetus provided to release rainfall at this time is not clear. The realization of potential instability developed in the afternoon hours has been used by DEXTER [1944] to explain greater nighttime rainfall. But here again there is no reason for 21h 00m to be the maximum hour. There is a possibility that the cessation of the sea breeze near this time may temporarily influence instability.

Conclusions--The diurnal variation of precipitation frequency at New York was found to have the same pattern throughout each of the summer months. Three primary maxima were exhibited on each of the curves near 07h 00m, 17h 00m, and 21h 00m. The morning maximum is considered to be a result of gradual radiational cooling of the atmosphere during the night hours and resultant instability.

The 17h 00m maximum may be attributed to afternoon insolational heating of the atmosphere. The 21h 00m maximum appears to have no adequate physical explanation. Detailed studies of thunderstorms, stability conditions, and the sea breeze in the New York area are required to further determine the physical conditions governing the time of release of rainfall at New York.

Acknowledgment--This paper is extracted from a Master of Science thesis completed at the College of Engineering, New York University. The author wishes to acknowledge the assistance of A. B. Kline, Official in Charge of the New York Meteorological Observatory, and H. A. Panofsky and J. E. Miller of the Department of Meteorology, New York University.

References

ALEXANDER, H. F., A study of the hourly precipitation at Oklahoma City, Okla., Mon. Wea. Rev., v. 66, pp. 126-131, 1938.

BYERS, H. R. (Director), The thunderstorm, Report of the Thunderstorm Project, Washington, D. C., 1949.

BYERS, H. R., and H. R. RODEBUSH, Causes of thunderstorms of the Florida peninsula, J. Met., v. 5, pp. 275-280, 1948.

COOK, A. W., The diurnal variation of summer rainfall at Denver, Mon. Wea. Rev., v. 67, pp. 95-98, 1939.

COUNTS, R. C., JR., Hourly frequency and intensity of rainfall at San Francisco, Calif., Mon. Wea. Rev., v. 61, pp. 225-228, 1933.

COX, H. J., and J. H. ARMINGTON, The weather and climate of Chicago, Geog. Soc. of Chicago, Chicago, 1914.

DEXTER, R. V., The diurnal variation of warm-frontal precipitation and thunderstorms, Q. J. R. Met. Soc., v. 70, pp. 129-137, 1944.

FASSIG, O. L., The climate and weather of Baltimore, Johns Hopkins Press, Baltimore, Md., 1907.

GREELEY, A. W., American weather, Dodd, Mead and Co., New York, 1888.

LONG, A. R., Hourly precipitation at Memphis, Tenn., Mon. Wea. Rev., v. 56, pp. 58-59, 1928.

MARTIN, H. H., Hourly distribution and intensity of precipitation at Kansas City, Mo., Mon. Wea. Rev., v. 77, pp. 153-159, 1942.

PETTERSSEN, S., Weather analysis and forecasting, McGraw-Hill, New York, 1940.

U. S. WEATHER BUREAU, Annual reports of the New York Meteorological Observatory, New York, 1898-1947.

U. S. WEATHER BUREAU, Thunderstorm rainfall, Hydrometeorological Report No. 5, Vicksburg, Miss., 1947.

U. S. WEATHER BUREAU, The climatic handbook for Washington, D. C., Tech. Pap. no. 8, Washington, D. C., 1949.

Division of Civil Engineering,
University of California,
Berkeley 4, California

(Communicated manuscript received January 22, 1951;
open for formal discussion until March 1, 1952.)

Transactions, American Geophysical Union Volume 32, Number 5 October 1951

THE DAMPING ACTION OF SUBMERGED BREAKWATERS

J. W. Johnson, R. A. Fuchs, and J. R. Morison

Abstract--The results of an experimental investigation on the damping action of submerged rectangular breakwaters are presented. The experimental data also are compared with published theories. A new theory is presented which compares more favorably with the experiments than the previous theories. Also given is a summary of all available published theoretical and experimental information on the damping action of trapezoidal and triangular breakwaters, reefs of various configurations, and plane barriers of various orientations.

Introduction--A submerged breakwater is a barrier which is constructed so that its top is at, or slightly below, the still-water level. Such a structure absorbs some of the wave energy by causing the waves to break prematurely. Some of the remaining energy is reflected and some transmitted shoreward. Submerged breakwaters usually are less costly to construct and maintain than the conventional type of breakwater which extends well above the highest expected tide stage.

The submerged breakwater is seldom used in a permanent harbor development because, even under ideal conditions, the degree of protection against wave action which it affords is less than that given by other types. In those localities where the tidal range is appreciable, an underwater structure might be relatively ineffective during high tides. Further, during low tides, the top might be above the still-water level, and the structure would therefore act as the conventional

Fig. 1--Photograph of wave action on natural reefs; note the damping action as the waves pass over the successive reefs

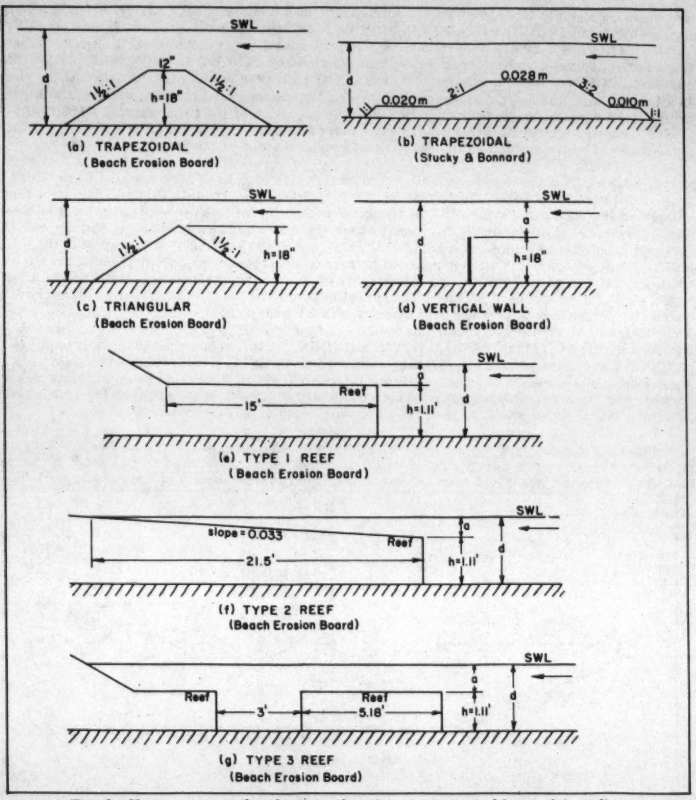


Fig. 2--Various types of underwater barriers investigated by model studies

type breakwater. As such, it would be subjected to much larger wave forces than it would have to withstand when submerged. For greatest effectiveness at all times, therefore, submerged breakwaters should be used in localities where the tidal range is relatively small.

In the known instances where underwater breakwaters have been constructed, they were built as an aid in the control of beach erosion [SOPER, 1940; BEACH EROSION BOARD, 1940]. These underwater barriers, constructed of sheet-steel piling, were placed offshore and parallel to the shoreline with the top of the piling at about still-water level. As a result of the use of these barriers, there was a reduction in the intensity of wave action on the shoreline and a consequent reduction in the rate of erosion of the shore. No data, however, are available on any comprehensive or quantitative study of the effect of these structures on wave action. An example of a natural underwater breakwater is the coral reef shown in Figure 1. This photograph demonstrates in a qualitative manner the effectiveness of such a barrier in reducing the intensity of wave action on the lee side of the reef.

The most reliable quantitative data on the effect of submerged breakwaters on wave action

are those obtained in laboratory model studies. In such studies, a wide variety of structure types has been investigated. The BEACH EROSION BOARD [1940] has reported on the damping effect of vertical walls and barriers with triangular and trapezoidal cross-sections (Fig. 2). Tests on a trapezoidal section also have been made in Switzerland by STUCKY and BONNARD [1937]. More recently, MORISON [1949a] has made an investigation of wave action over rectangular barriers. In all these past studies, the experiments were on two-dimensional models, wherein the wave crests were parallel to the barrier axis. With the exception of the experiments of MORISON [1949a], where rectangular breakwaters were placed on both a horizontal and a sloping bed, the same depth of water existed on the seaward and inshore sides of the structures.

In addition to the above investigations, model studies also have been made of wave action over various idealized reefs [BEACH EROSION BOARD, 1944]. As shown in Figure 2, various reefs investigated included three types: (1) an abrupt discontinuity followed to shoreward by a horizontal shelf, (2) an abrupt discontinuity followed to shoreward by a uniformly shoaling bottom, and (3) an abrupt discontinuity followed by a horizontal shelf, a depression, and a continuation of the horizontal shelf. These experiments were concerned primarily with the change in wave length after the waves passed the reef's seaward edge. No information is given on the reduction in wave height after the waves passed over the reef. A theoretical treatment of the change in height after waves have passed over a reef of type 1, however, has been made by LAMB [1945, p. 262]. Other theoretical work included wave action over submerged rectangular barriers by JEFFREYS [1944], submerged plane vertical barriers by DEAN [1945a], URSELL [1947], and JOHN [1948], submerged plane horizontal barriers by HEINS [1950], and submerged circular cylinders by URSELL [1950]. The problem of reflections at inclined plane barriers has been analyzed by DEAN [1945b]. The discussion to follow presents a summary of the previously unpublished data of MORISON [1949a] and compares the results, where possible, with theory as well as the previous model studies on other types of structures.

Experimental equipment procedure--To determine the general effectiveness of rectangular underwater breakwaters in reducing wave action, a series of model studies was made in the one-foot wave channel in the Fluid Mechanics Laboratory at the University of California, Berkeley.

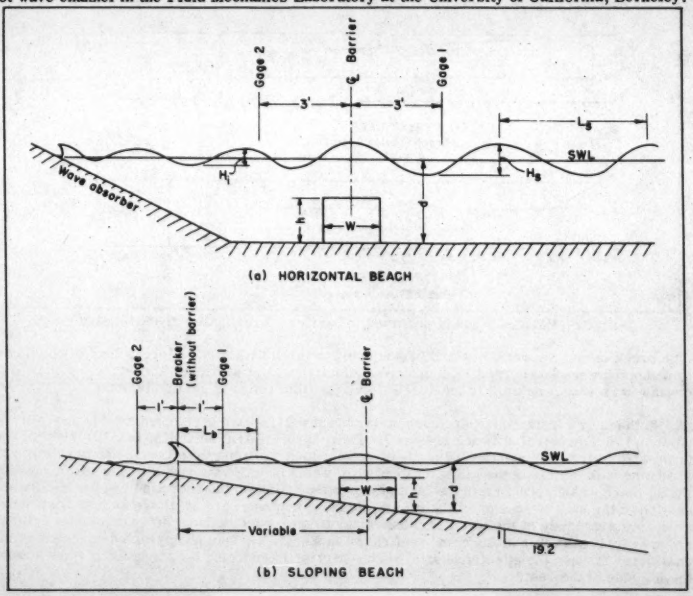


Fig. 3--Experimental equipment for tests on submerged rectangular barriers

The variables in these tests were the height and width of the barrier, the depth of water. and the wave height and length. Tests were made with both a horizontal bottom and a beach with a slope of 19.2/1 (Fig. 3). The barriers were assembled layer upon layer of plywood until their height reached the elevation of the still-water level. Barrier widths of 0.33, 0.67, and 1.00 ft were used in the tests with a horizontal bottom, and widths of 0.31 and 0.60 ft were used in the tests on the sloping beach. In the latter tests, four positions of the barrier were used in relation to the breaker position. These positions were 20, 30, 40, and 60 inches seeward of the breaker point. Shoreward from the barriers, a crushed rock beach was provided to absorb the waves which passed over the barrier. Approximately 70 runs, covering a large range of the variables, were made with a horizontal bottom, and about ten runs were made with the sloping bottom.

Wave heights were measured for each barrier height, as shown in Figure 3, by means of wire resistance elements [MORISON, 1949b]. This recording system consisted of two pairs of wire resistance elements, each connected in series with an oscillograph and in parallel with separate transformers. The elements were mounted on point gages and calibrated by lowering them to successive positions in the water. During a test, only the fifth to tenth waves were recorded, in order to permit the first few irregular waves to pass the recording elements and to avoid inclusion of waves reflected from the beach. During some tests, motion pictures of the wave action were taken with a 35-mm camera.

In the tests with a horizontal bottom the test procedure differed slightly from that employed with a sloping bottom. For the tests with a horizontal bottom, a "steady-state" run first was made. This type of run consisted of first measuring wave heights by gages 1 and 2 (Fig. 3a) with no barrier in place. The average wave height so obtained was designated as the seaward wave height, H_s (see the list of symbols in Appendix 1). Also from the oscillograph record, the wave period and the time for the wave to travel from gage 1 to gage 2 were determined. From these latter data, the wave length was computed. The barrier next was placed in position (Fig. 3a) and the wave height then measured at gage 2 after each increase in barrier height. In both the steady-state and the test runs with the barrier in place, the wave height, H_l, was taken as the average height of the fifth to tenth waves as measured on the oscillograph record.

In the experiments on the sloping beach, the resistance elements were located equidistant from the point where the waves broke when no barrier was in place (Fig. 3b). With no barrier in place, a steady-state run was made for each wave condition as discussed above in the tests on a horizontal bottom. From the oscillograph record, the height, H_s, was taken to be the height at gage 1. Also from the oscillograph record, the wave period and the travel time of the waves between gages 1 and 2 (Fig. 3b) were determined, from which data the wave length near the breaker was computed. For each wave condition, barriers were placed at various multiples of the wave length seaward from the normal point of breaking. For a given barrier position, the barrier height was varied by adding successive layers of plywood. Wave height then was measured at gage 1 for each test condition, and the height, H_l, was taken as the average of the fifth to tenth waves passing the barrier.

With the above-determined values of water depth, barrier height and width, and wave characteristics, the values of the various dimensionless terms discussed below were computed for each run.

Experimental results--As described above, the wave characteristics, barrier dimensions, and other features as illustrated in Figure 3, were measured during each run. A consideration of the various terms shows that the following dimensionless groupings can be used to represent the relationship between the transmission coefficient, H_l/H_s, and the other variables, that is,

$$H_l/H_s = f\,(H_s/L_s, W/L_s, h/d, d/L_s)$$

To demonstrate the relative importance of these variables, certain of the data have been summarized in Figures 4 to 7 inclusive. Figure 4 shows the general effect of the wave steepness, H_s/L_s, on the transmission coefficient, H_l/H_s, for various relative barrier heights, h/d, and approximately constant values of relative depth, d/L_s, and relative barrier width, W/L_s. The two sets of experimental data shown in this figure indicate that a barrier of a given relative height, h/d, is more effective in damping relatively steep waves than relatively flat waves, which is to be expected since a wave near the critical steepness for breaking can be easily "tripped" and made to break by any outside disturbance [O'BRIEN, 1949]. This effect of steepness becomes relatively small when the top of the barrier is at or slightly above the still-water level. This conclusion also has been established theoretically by JEFFREYS [1944] for waves of small amplitude in shallow water. The theoretical relationship of Jeffreys is plotted in Figure 8 with the transmission coefficient, H_l/H_s,

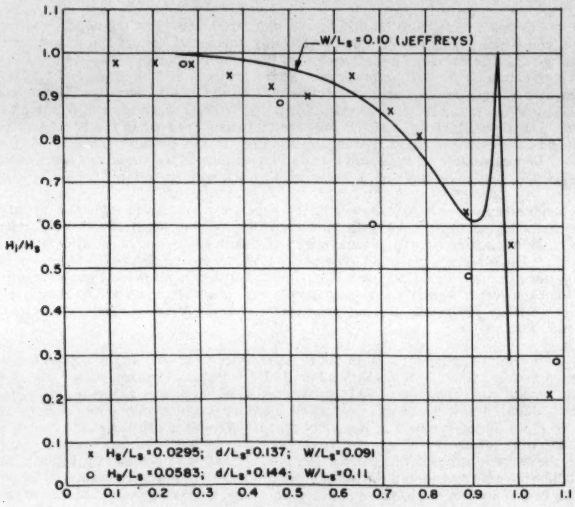


Fig. 4--Effect of wave steepness on wave action over a rectangular underwater barrier

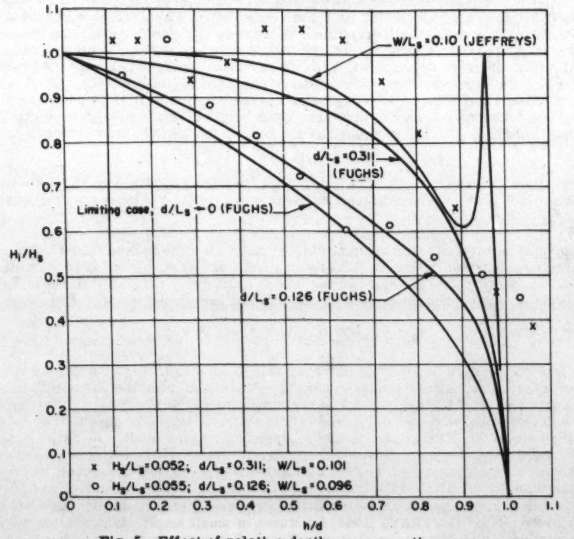

W/Ls = 0.10 (JEFFREYS)
d/Ls = 0.311 (FUCHS)
Limiting case, d/Ls = 0 (FUCHS)
d/Ls = 0.126 (FUCHS)
Hi/Hs
h/d
x Hs/Ls = 0.052; d/Ls = 0.311; W/Ls = 0.101
o Hs/Ls = 0.055; d/Ls = 0.126; W/Ls = 0.096

Fig. 5--Effect of relative depth on wave action over a rectangular underwater barrier

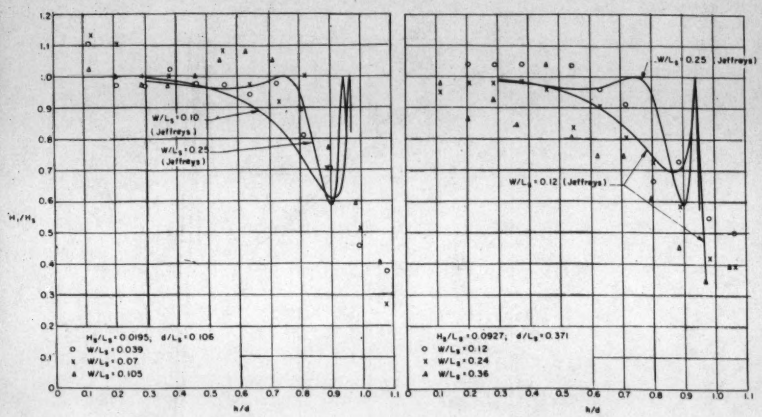


Fig. 6--Effect of relative width of a structure on wave action over a rectangular underwater barrier

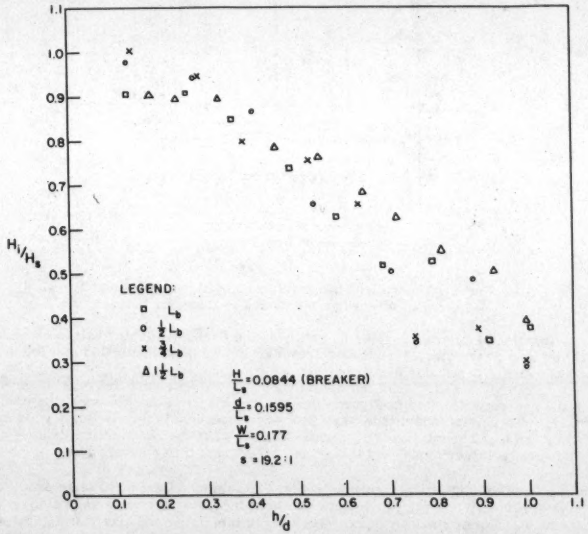


Fig. 7--Effect of barrier position on wave action over a rectangular underwater barrier

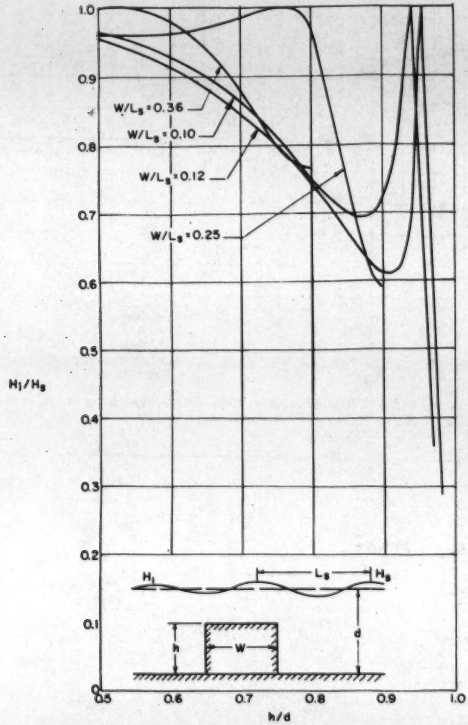


Fig. 8-- Theoretical transmission coefficients obtained by Jeffreys for wave action over a rectangular barrier

shown as a function of relative barrier height, h/d, and various selected values of relative width, W/L_s, shown as a parameter. This theory shows the interesting conclusion that the most effective damping action for a particular barrier height occurs when the width of the barrier is $1/4\sqrt{1 - h/d}$, $3/4\sqrt{1 - h/d}$, $5/4\sqrt{1 - h/d}$, . . . of the wave length, L_s. To compare Jeffreys' theoretical relationship with the experimental data in Figure 4 the theoretical curve for the condition when $W/L_s = 0.10$ is shown. For the smaller amplitude wave (low wave steepness) there is fairly good agreement between theory and experiment; however, for the steeper wave the assumptions underlying the theoretical treatment no longer apply, and theory and experiment differ greatly.

In a presentation similar to Figure 4, Figure 5 shows the effect of relative depth, d/L_s, on the transmission coefficient for two conditions where the wave steepness and relative dimensions of the barrier were approximately equal. The data in this figure indicate that a greater damping effect is obtained when the relative depth, d/L_s, becomes small. This conclusion appears reasonable and might be predicted qualitatively if it is recognized that a larger per cent of the wave energy is concentrated in the upper layers of the depth for large d/L_s values than for low values of d/L_s. Hence this energy can "spill over" the top of the barrier more easily than when the energy is more uniformly distributed throughout the depth as in the case of waves with small values of

d/L_s. As in the case with the data shown in Figure 4, once the top of the barrier is located near still-water level, the effect of d/L_s on the transmission coefficient becomes unimportant. Again for comparative purposes, Jeffreys' theoretical curve for a value of $W/L_s = 0.10$ is presented. Also shown are curves as obtained by the theory presented in Appendix 2 and discussed below.

In connection with the "spill over" effect mentioned above, note that by estimating the reflected wave energy and assuming conservation of both energy and period, one is led directly to simple formulas for the transmission coefficients. As a first approximation the energy transmitted forwarded with the incident wave per unit time and below depth d - h is assumed to be totally reflected. The calculations, given in Appendix 2, show that the reflection decreases the wave height while the shoaling action over the barrier increases the wave height and decreases the wave length. The net effect is that the transmission coefficient ranges from 1 to 0 as h/d ranges from 0 to 1. As to be expected, the transmission coefficient drops rather sharply in going shoreward from the barrier. The wave length increases to its original value. The agreement with experiment in Figure 5 is good. A comparison of the theoretical curves with the experimental points in Figure 5 indicates that Jeffreys' theory, as might be expected, is seriously in error for relatively steep waves.

As predicted theoretically and illustrated in Figure 8, an important variable determining the effectiveness of an underwater breakwater is the relative width, W/L_s, of the structure. Experimental data on this factor are shown in Figure 6 where the transmission coefficient is plotted against the relative height (as in Fig. 4 and 5) with the relative width as a parameter. The plot in Figure 6a pertains to a wave of relatively low steepness (and also with a low d/L_s value), whereas Figure 6b pertains to a wave with a relatively high steepness (and also with a high d/L_s value). Also shown in Figure 6 for comparative purposes are Jeffreys' theoretical curves for relative barrier widths, W/L_s, of 0.25 and 0.10 in Figure 6a and 0.25 and 0.12 in Figure 6b. The data shown in Fig. 6a tend to confirm this theoretical relationship (Fig. 8), since the experimental conditions closely approximate the theoretical assumptions of small amplitude waves in shallow water.

With respect to Figure 6b, which presents the results of tests with a high wave steepness, it is noted that the transmission coefficient appears to be more sensitive to barrier width than was the case in Figure 6a; however, it must be recognized that the barriers had relatively large widths in the runs presented in Figure 6b as compared to those in Figure 6a. As might be expected, the data shown in Figure 6b indicate that the wider the barrier (higher values of W/L_s), the better is the damping action. Comparison of the experimental data with Jeffreys' theoretical curves shows comparatively good agreement for values of $W/L_s = 0.12$ and $W/L_s = 0.24$. Poor agreement, however, is observed between theory and experiment for $W/L_s = 0.36$. The experimental data show that a greater degree of damping can be obtained with the wider barriers than the theoretical maximum shown in Figure 8. The fact that the wave in Figure 6b was not a wave of small amplitude probably explains the divergence between theory and experiment.

Other information that is of considerable interest is the effect of barrier position on wave damping. In this respect "barrier position" pertains to the distance of the barrier from the point of breaking when no barrier was in place. The tests to yield information on this phase of the problem were conducted on a uniformly sloping solid beach (19.2/1) where the waves actually broke on the test beach. The method of conducting these tests is described above in connection with Figure 3b. The additional parameter in these tests, compared to those described above for a horizontal bed, was the location of the barrier, expressed as a multiple (or fraction) of the wave length as measured in the surf zone. Figure 7 shows typical results from these tests wherein the transmission coefficient is plotted against relative barrier height, with barrier position as a parameter. The data shown in Figure 7 were obtained with a barrier width of about 1/6 wave length. Since the measurements were made in or near the breaker zone, the wave steepness was up to the limiting value. For the conditions summarized in Figure 7, it appears that the effect on the transmission coefficient, in general, is relatively insensitive to barrier position. As the larger relative barrier heights, h/d, are approached, however, a slightly better damping action appears to result if the barrier is located at or near one wave length from the breaker line. This would indicate that waves could be effectively "tripped" by an underwater breakwater and made to break and lose much of their energy if the barriers are located a wave length or more seaward from the normal breaking point. For the sloping beach, as well as in the case with the experiments on a horizontal bottom, the most effective damping actinn of an underwater breakwater occurs when the top of the structure is placed at the still-water level. On natural beaches the bottom usually can be assumed to be horizontal over a distance of a wave length or more, with the result that the various data presented for tests on a horizontal bottom can be considered to apply with reasonable accuracy for most natural beaches.

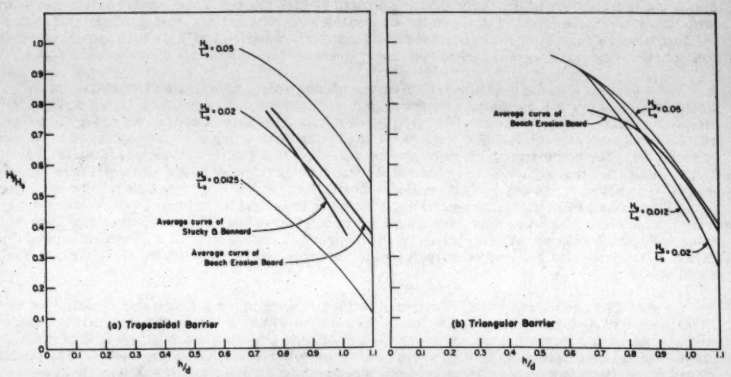


Fig. 9--Transmission coefficients for trapezoidal and triangular underwater barriers [BEACH EROSION BOARD, 1940]

Other investigations--As mentioned above, previous model studies have been conducted on underwater breakwaters with triangular and trapezoidal cross-sections as well as on barriers which consisted of a thin vertical wall (Fig. 2d). These data have been summarized by the BEACH EROSION BOARD (BEB) [1940]; however, in that analysis no attempt was made to consider all of the dimensionless factors discussed in the above section. Consequently, the BEB data were re-analyzed to conform to the method of presenting the data for rectangular barriers as discussed above. The number of runs for each barrier shape tested by the BEB was relatively small; hence, it was necessary to cross-plot the original data to permit a presentation of the type of curves given above. Figure 9 shows the transmission coefficient as a function of relative barrier height and wave steepness for the triangular and trapezoidal sections tested by the BEB (Fig. 2a-2c). Also shown on these plots are the average curves as presented by the BEB where the effect of wave steepness was omitted. The wide scatter of points in the BEB original plots, particularly for the trapezoidal section, probably was due to the effect of wave steepness. The cross-plots of the original BEB data show the effect of wave steepness (Fig. 9). This effect is relatively great in the case of the trapezoidal breakwater (Fig. 9a), but appears relatively small in the case of the triangular section (Fig. 9b). Note in the two plots shown in Figure 9 that with the trapezoidal and triangular barriers a greater degree of damping was observed for the lower wave steepnesses than for the steeper waves. The opposite effect was noted, however, for the rectangular barrier (Fig. 4).

Examination of the BEB data shows that for the waves of low steepness the relative depth, d/L_s, also was small; hence, as might be expected from a consideration of Figure 5, the relative position of the curves shown in Figure 9 may be dictated more by the effect of relative depth than by wave steepness. The BEB data, however, were too meager to permit a separation of the effects of these two factors. Because of the small amount of data for the vertical wall no attempt has been made to summarize herein these results in curve form. Of interest in connection with vertical walls are the theoretical treatments of DEAN [1945a], URSELL [1947], and JOHN [1948] wherein the transmission coefficient is given for the two types of fixed vertical barriers shown in Figure 10a. Plots of both transmission and reflection coefficients for these two types of barriers as determined by Dean and Ursell are shown in Figure 11. The reflection coefficient in the above instance is defined as the ratio of the wave heights (at a great distance from the barrier) of the reflected and incident waves.

In connection with wave action over an underwater reef, this problem has been approached from both theoretical and experimental standpoints. LAMB [1945, p. 262] has considered theoretically the case of wave action over a reef (Fig. 10d) with shallow water in front of the barrier. In this case expressions for both the transmission coefficient and the reflection coefficient were determined. These coefficients are shown in Figure 12 as a function of the relative height of the reef. Also shown in this figure are curves of the transmission coefficient as plotted from the

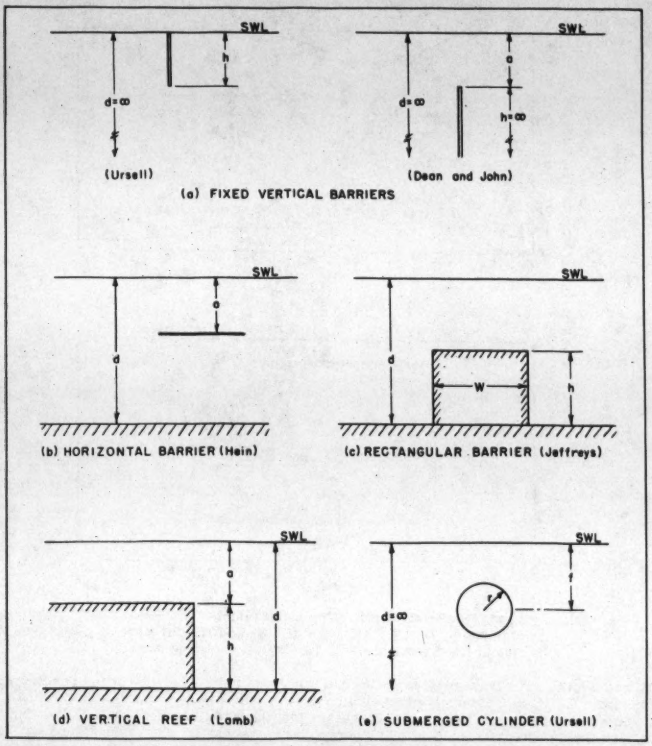


Fig. 10--Various types of underwater barriers investigated from theoretical considerations

theory presented in Appendix 2. The two curves shown pertain to the cases where d/L_S approaches zero and $d/L_S = 0.311$. The theoretical results are totally different. No experimental data are available for comparison in this situation.

The only known experimental work approximating the theoretical treatment of LAMB [1945, p. 262] is that of the BEACH EROSION BOARD [1944]. The various reef arrangements that were tested are shown in Figures 2e-2g. These investigations were concerned primarily with the change in wave length after waves passed over a reef, and no information was given on the transmission coefficient. Of interest in these tests, however, was the establishment of a criterion for determining whether a wave would pass over a reef as a single wave or break into a multiplicity of waves as illustrated in Figure 1. This criterion for a regular transition is that when the value of the term $\sqrt{H_o L_o}/a$ is less than 2.0 the transition is regular. For larger values of this term a wave passing the reef will break into a number of waves.

Experiments have been made by HAMILTON [1950] on the damping action of plane sloping surfaces which extend below the still-water level only a portion of the total depth. In such an instance, some wave energy is transmitted to the lee side by the waves passing beneath the structure. The upper edge of the plane surface in these tests was located above, at, and below the

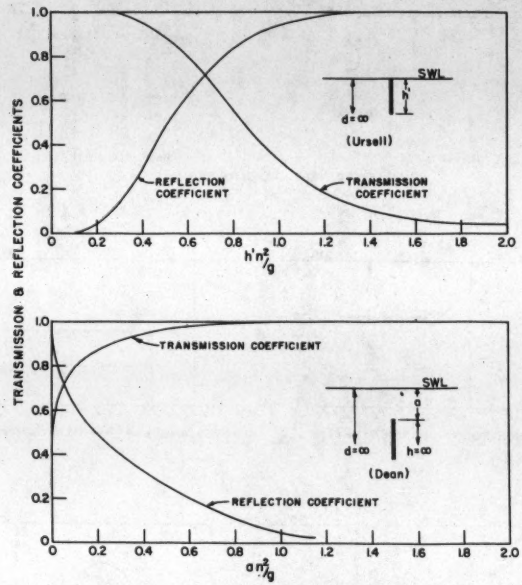


Fig. 11--Theoretical reflection and transmission coefficients obtained by DEAN [1945a] and URSELL [1947] for wave action at fixed vertical barriers ($2\pi/n$ is the wave period)

still-water level. The transmission coefficient was found to be a function of the relative width of the surface, L_s/B, with the angle of inclination of the surface being a parameter (Fig. 13). From the scatter of the points in this figure, it appears that the wave steepness and relative depth perhaps also should have been considered as parameters. As may be seen from Figure 13c, the submerged plane was relatively ineffective in damping the waves, whereas when the upper edge of the plane was at or above the still-water level (Fig. 13a and 13b), effective damping action was obtained.

Conclusions--Within the limits of the experiments on rectangular underwater barriers, the following conclusions can be stated:

(1) For a given relative barrier dimension and relative depth, the transmission coefficient is greater (small damping action) for relatively flat waves than relatively steep waves. Also, for a given relative barrier dimension and wave steepness, the transmission coefficient is greatest for large relative depths.

(2) A relatively wide barrier has a better damping action (low transmission coefficient) than a relatively narrow barrier, especially for relatively steep waves.

APPENDIX 1--NOTATION

- a = depth of barriers below still-water level
- B = width of sloping barrier
- d = depth of water
- g = acceleration of gravity
- H_i = wave height inshore from barrier

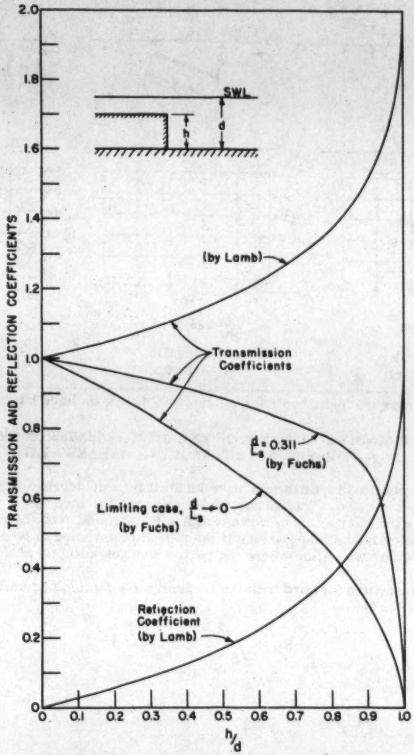


Fig. 12--Theoretical reflection and transmission coefficients for wave action on a vertical reef

H_S = wave height seaward from barrier
H_O = wave height in deep water
h = height of barrier
L = wave length
L_S = wave length seaward from barrier
L_b = wave length at breaker
L_o = wave length in deep water
s = beach slope
T = wave period
W = width of barrier
θ = angle of inclination of sloping barrier

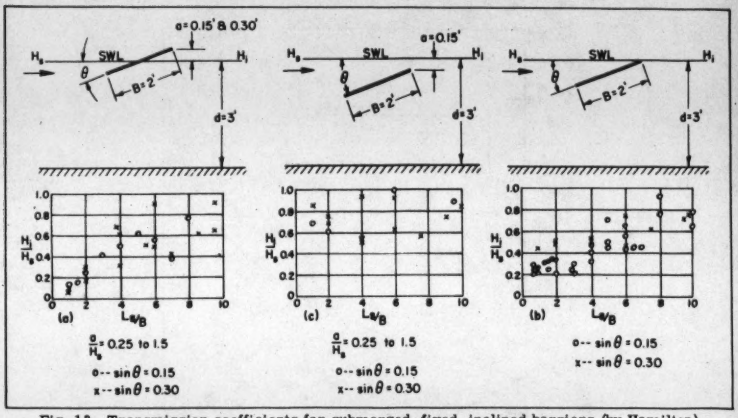


Fig. 13--Transmission coefficients for submerged, fixed, inclined barriers (by Hamilton)

APPENDIX 2--THEORY OF ENERGY TRANSMISSION OVER A SUBMERGED RECTANGULAR BREAKWATER

The energy transmitted forward in a wave incident on a submerged barrier is partially transmitted and partially reflected. The transmitted energy is reformed into a wave motion influenced by the shoaling over the barrier. The wave length will decrease over the barrier and lengthen to the original value after leaving the barrier if the period is assumed to be constant. We exclude the cases of non-regular transition where the period changes abruptly at the edge of the barrier.

The energy transmitted forward with the incident wave motion per unit time and below a depth d - h is [LAMB, 1945]

$$E_R = -\int_d^{d-h} (p\,\partial\phi/\partial x)\,dy$$

where

$$p = \rho(\partial\phi/\partial t - gy)$$

$$= \rho g H \cosh[k(y+d)] \cos(kx - \sigma t)/2\cosh kd$$

$$k = 2\pi/L$$

$$\sigma = 2\pi/T$$

Substituting and carrying out the integration we find for the time average of E_R

$$\overline{E_R} = g\rho H^2 C \sinh 2kh\,(1 + 2kh/\sinh 2kh)/16 \sinh 2kd$$

The total average energy transmitted per unit time in the incident wave is obtained by setting h = d or

$$\overline{E_i} = g\rho H_s^2 C\,(1 + 2kd/\sinh 2kd)/16$$

The average energy transmitted per unit time over the barrier is

$$\overline{E_T} = g\rho H_s^2 C(1 + 2kd/\sinh 2kd)[1 - \sinh 2kh(1 + 2kh/\sinh 2kh)/\sinh 2kd(1 + 2kd/\sinh 2kd)]/16 \quad . . \quad (1)$$

There are two cases to be considered here, if the wave period is assumed to remain constant. The wave length and wave velocity depend upon the depth according to the relations

$$k = (\sigma^2/g) \coth kd$$
$$C = (g/\sigma) \tanh kd \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Case 1--Tne transmitted wave is measured in water of depth d shoreward of the barrier. In this case k and C are equal to their original values for the incident wave. Since $\overline{E_T}$ must have the same form as $\overline{E_I}$ the transmission coefficient is

$$(H_I/H_s)_d = \sqrt{1 - (\sinh 2kh)\, n\,(h)/(\sinh 2kd)\, n\,(d)} \quad \ldots\ldots\ldots\ldots\ldots (3)$$

where

$$n\,(h) = (1 + 2kh/\sinh 2\,kh)/2$$

Case 2--The transmitted wave is measured over the barrier as for a reef of type 1. The transmitted wave is subject to shoaling over the barrier, its height and length varying in such a way that energy and wave period are conserved. The average energy transmitted per unit time over the barrier can be written in the form

$$\overline{E_T} = g\rho H_I^2\, C_a\, (1 + 2\,k_a a/\sinh 2\,k_a a)/16 \quad \ldots\ldots\ldots\ldots\ldots\ldots (4)$$

where the subscript a refers to conditions in water of depth a = d - h. Comparing (1) and (4) we find for the transmission coefficient

$$(H_I/H_s)_a = S\,(H_I/H_s)\,d$$

$$S = \text{shoaling factor} = \sqrt{C_d\, n_d\, (d)/C_a\, n_a\, (a)}$$

The shoaling factor can be readily determined from the publication of WIEGEL [1948]. It gives the relative wave height in a wave moving from depth d to depth d - h without reflection.

Two important special cases merit individual attention. For shallow water ($kd \ll 1$) one finds

$$(H_I/H_s)_d \cong \sqrt{1 - h/d}$$
$$(H_I/H_s)_a \cong \sqrt[4]{1 - h/d}$$

For deep water ($kd \gg 1$) one finds

$$(H_I/H_s)_d \cong \sqrt{1 - 4\, e^{-2kd} (\sinh 2kh)\, n\,(h)}$$

which is nearly equal to unity unless the barrier is near the free surface in which case

$$(H_I/H_s)_d \cong \sqrt{1 - e^{-2ka}}$$

For shallow water and for deep water in case the barrier is near the surface, the transmission coefficients are the same as if it is assumed initially that a fixed fraction of the total energy associated with the incident wave is reflected.

References

BEACH EROSION BOARD, A model study of the effect of submerged breakwaters on wave action, Tech. Memo. 1, Chief of Engineers, U. S. War Dept., 1940.

BEACH EROSION BOARD, A method for determining depths over bottom discontinuities, Tech. Memo. 5, Chief of Engineers, U. S. War Dept. 1944.

DEAN, W. R., On the reflection of surface waves by a submerged plane barrier, Grt. Brit. Ministry of Supply, Wave Report 8, 1945a.

DEAN, W. R., On some cases of the reflection of surface waves by an inclined plane barrier, Grt. Brit. Ministry of Supply, Wave Report 13, 1945b.

HAMILTON, W. S., Forces exerted by waves on a sloping board, Trans. Amer. Geophys. Union, v. 31, pp. 849-855, 1950.

HEINS, A. E., Water waves over a channel of finite depth with a submerged plane barrier, Can. J. Math., v. 2, pp. 210-222, 1950.

JEFFREYS, H., Note on the offshore bar problem and reflection from a bar, Grt. Brit. Ministry of Supply, Wave Report 3, June 1944.

JOHN, F., Waves in the presence of an inclined barrier, Comm. Appl. Math., v. 1, pp. 149-200, 1948.

LAMB, H., Hydrodynamics, 6th ed., 1945.

MORISON, J. R., Model study of wave action on underwater barriers, Inst. Eng. Res., Univ. Calif., Berkeley, Report HE-116-304, 1949a.

MORISON, J. R., Measurement of heights by resistance elements, Bull. Beach Erosion Board, v. 3, no. 3, pp. 13-22, 1949b.

O'BRIEN, M. P., The causes of plunging and spilling breakers, Bull. Beach Erosion Board, v. 3, no. 3, pp. 7-10, 1949.

SOPER, G. A., Beach erosion studies (a discussion), Trans. Amer. Soc. Civ. Eng., v. 105, pp. 893-895, 1940.

STUCKY, A., and D. BONNARD, Contribution to the experimental study of marine rock fill dikes, Bull. Technique de la Suizze Romande, August 1937 (also see summary in Tech. Memo. 1, Beach Erosion Board, 1940).

URSELL, F., The effect of a fixed vertical barrier on surface waves in deep water, Proc. Cambridge Phil. Soc., v. 43, pp. 374-382, 1947.

URSELL, F., Surface waves in deep water in the presence of a submerged circular cylinder, Proc. Cambridge Phil. Soc., v. 46, pp. 141-158, 1950.

WIEGEL, R. L., Diagrams and tables of relationships commonly used in investigations of surface waves, Bull. Beach Erosion Board, Spec. Issue 1, July 1948.

Department of Engineering,
University of California,
Berkeley, California

(Manuscript received April 16, 1951; presented by title at the Thirty-Second Annual Meeting, Washington, D. C., April 30, 1951; open for formal discussion until March 1, 1952.)

Transactions, American Geophysical Union Volume 32, Number 5 October 1951

GRAPHICAL DETERMINATION OF SPECIFIC-VOLUME ANOMALY AND CURRENT

E. B. Callaway

Abstract--The derivation is described of a specific-volume anomaly nomogram and an alignment chart for finding the relative current from the dynamic-depth anomaly difference, the distance between oceanographic stations, and the mean latitude. An evaluation is made of the degree of accuracy obtainable by the use of the nomograms as compared to the use of tables.

Introduction--The development of a graphical method for the determination of specific-volume anomaly and current was undertaken in the Division of Oceanography of the U. S. Navy Hydrographic Office because of the necessity for the reduction of a large number of serial observations of temperature and salinity versus depth in the evaluation of the relative current from the isobaric slope. Particularly tedious in this process are the determination of specific volume or specific-volume anomaly from the temperature-salinity-depth data, and the determination of relative current from the dynamic-depth differences deduced from these specific volumes or specific-volume anomalies. In order to reduce this time and labor, nomograms to replace the usual specific-volume anomaly tables and an alignment chart to solve the equation for current from isobaric slope were developed A definite saving in time in comparison to the use of tables, with no loss in accuracy of results, was found. The chief advantage of the graphical method was found to be the elimination of tabular interpolation by the nomograms and the elimination by the use of the alignment chart of the tedious evaluation of the relative current equation.

Nomograms of specific-volume anomaly--The nomograms of specific-volume anomaly are in two parts, the terms in the expression for the anomaly which are independent of pressure ($10^5\Delta_{st}$) being shown in one series and the terms involving the pressure correction $10^5\delta_{tp}$ and $10^5\delta_{sp}$ on two additional sheets.

The first series of charts shows on rectangular Cartesian coordinates the variation with temperature and salinity of the $10^5\Delta_{st}$ term of the specific-volume anomaly by using temperature as parameter, $10^5\Delta_{st}$ as ordinate, and salinity as abscissa, the ordinate values being calculated from (1).

The pressure terms $10^5\delta_{tp}$ and $10^5\delta_{sp}$ are shown as two families of curves one above the other on the same sheet of rectangular Cartesian coordinates, the first family having $10^5\delta_{tp}$ as ordinate, depth in meters as abscissa, and temperature as parameter; and the second family having $10^5\delta_{sp}$ as ordinate, depth in meters as abscissa, and salinity as parameter. The scale on all the charts is 0.1 inch equals one unit of the ordinate, that is, one unit in the fifth place of specific-volume anomaly. In the $10^5\Delta_{st}$ group, the abscissa scale is 0.1 inch equals 0.01 °/oo salinity, while in the $10^5\delta_{tp}$ and $10^5\delta_{sp}$ groups the scale of the abscissa is 0.1 inch equals ten meters depth. The range of values of temperature, salinity, and depth shown on these charts is: temperature, -2° C to +30° C inclusive; salinity, 30 °/oo to 38 °/oo inclusive; and depth 0 to 5000 m inclusive.

In order to cover the above range at the scale indicated it was necessary to make the charts on 14 sheets, sheets 1 to 12 inclusive for the $10^5\Delta_{st}$ term and sheets A and B for the pressure terms. Figure 1 is an index chart which shows the range of values covered by the different sheets.

Current computation nomogram--The current computation nomogram consists of an M-type alignment chart with four scales and an index line. Alignment charts of this type are made up of a combination of two simple diagrams, each consisting of two parallel scales and a third oblique to them, being related to each other through the common central vertical index line. Each of the component diagrams solves an equation of the form $f_1(u) = f_2(v) \times f_3(w)$ by means of the geometrical relationship of similar triangles and is constructed by drawing two oppositely directed vertical parallel axes with the third oblique to them. On the four scales are shown the values given in Table 1.

Figure 2 shows the current computation nomogram.

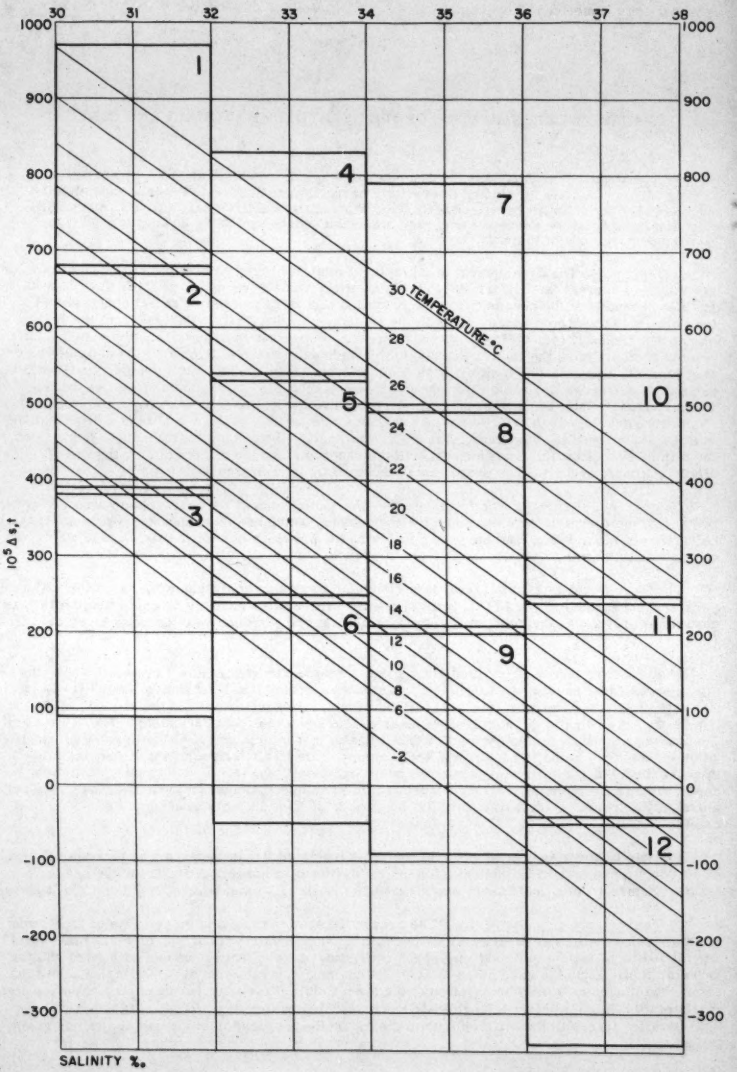


Fig. 1--Index of specific-volume anomaly diagrams

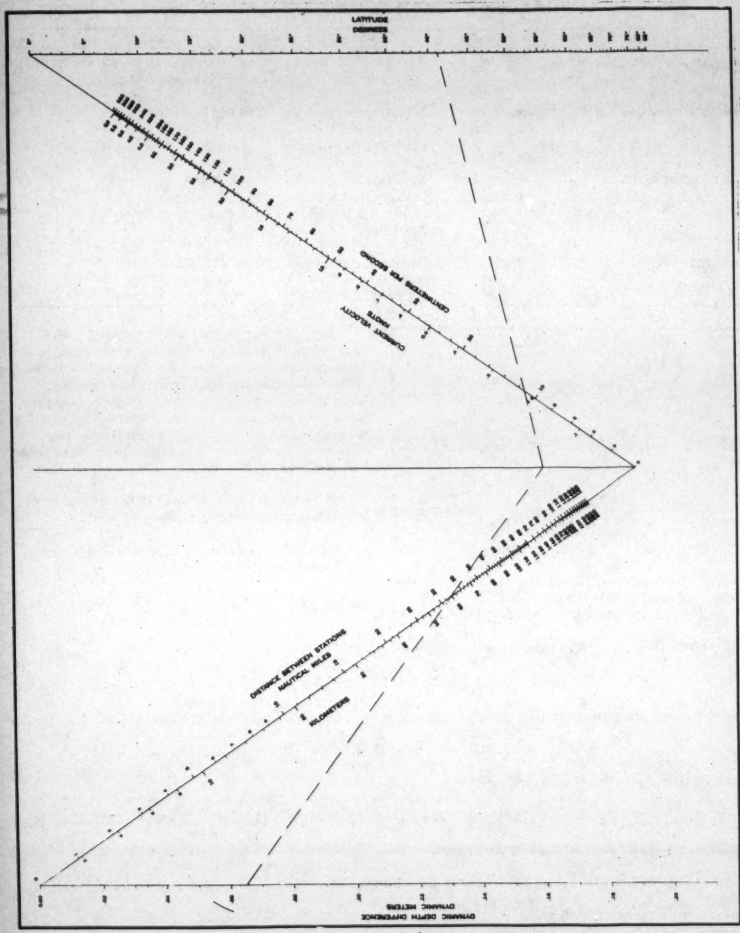


Fig. 2--Current computation nomogram showing method of finding current from dynamic-depth anomaly difference

Accuracy of specific-volume anomaly nomograms

There are three factors that limit the theoretical accuracy or precision of the nomograms, namely, (1) scale, (2) use of straight temperature lines, and (3) use of linear (first order) interpolation between parametric isopleths.

Scale--The scale of 0.1 inch equals one unit of the ordinate scale makes possible the reading of this scale to 0.1 of the unit, that is, to the sixth decimal place of specific-volume anomaly.

Table 1- Characteristics of current computation nomogram

Values	Units	Scale	Range
Dynamic depth difference	dyn m	Linear; 0.01 dyn m = 0.75 in	0.00 to 0.20 (can be varied at will by moving decimal point)
Distance between stations	naut mi and km	Non-linear; in central portion 1 naut mi = 0.3 in = 2 km	0 to 160 naut mi
Current velocity	knots and cm/sec	Non-linear; in central portion 0.1 knot = 0.5 in = 5 cm/sec	0 to 6 knots
Latitude	degree	Non-linear; in central portion 1° = 0.2 in	0° to 85°

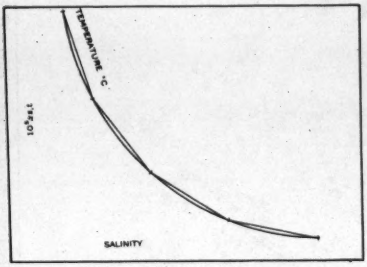


Fig. 3--Actual curves and chords (curvature greatly enlarged)

Use of straight temperature lines--The charts are drawn by connecting with straight lines points evaluated for even parts per thousand salinity at the indicated temperatures. Thus the charts show a series of 1 °/oo chords instead of the actual curve. Figure 3 shows how the actual curve of $10^5\Delta_{st}$ is related to the chords which are the isopleths shown on sheets 1 through 12 (shown on Fig. 1).

It remains to show how far the actual curve departs from the chord at its midpoint.

The relation between σ_t and Δ_{st} (the quantity shown on the charts) is given by

$$\Delta_{st} = 0.0273569 - 10^{-3}\,\sigma_t/(1 + 10^{-3}\,\sigma_t) \quad \ldots (1)$$

Differentiating (1) with respect to σ_t, one obtains

$$d\,\Delta_{st}/d\,\sigma_t = -\,10^3/(10^3 + \sigma_t)^2 \quad \ldots (2)$$

and differentiating the equation for σ_t in terms of σ_o and constants from KNUDSEN [1901] yields

$$d\,\sigma_t/dCl = (d\,\sigma_o/dCl)\,(2\,B_t\,\sigma_o + 1 - A_t) \quad \ldots (3)$$

Substituting the value of $d\,\sigma_o/dCl$ gives

$$d\,\sigma_t/dCl = (1.4708 - 0.00314\,Cl + 0.0001194\,Cl^2)\,(2\,B_t\,\sigma_o + 1 - A_t) \quad \ldots (4)$$

Multiplying (4) by (2) and then by 10^5 gives

$$d\,10^5\,\Delta_{st}/dCl = -\,10^8\,(1.4708 - 0.00314\,Cl + 0.0001194\,Cl^2)\,(2\,B_t\,\sigma_o + 1 - A_t)/(10^3 + \sigma_t)^2 \quad \ldots (5)$$

and multiplying by dCl/dS gives

$$d\,10^5\,\Delta_{st}/dS = (-81{,}484{,}764.5 - 173{,}961.2\,Cl + 6614.96\,Cl^2)\,(2\,B_t\,\sigma_o + 1 - A_t)/(10^3 + \sigma_t)^2 \quad \ldots (6)$$

in which B_t and A_t are the constants tabulated in Knudsen. They vary with temperature only. Equation (6) shows that the parametric isopleths of temperature on the specific-volume anomaly nomograms are not straight lines, but that their slope varies with salinity (the Cl terms in the numerator of (6)). The minus sign indicates that they slope downward toward the right. The fact that $d^2\,10^5\,\Delta_{st}/ds^2$ is positive for all values of S shows that this curve is concave from above. By evaluating this slope at various points over the nomograms and comparing with the slope of the chord at the same point, the amount of the departure of the curve from the chord at its midpoint

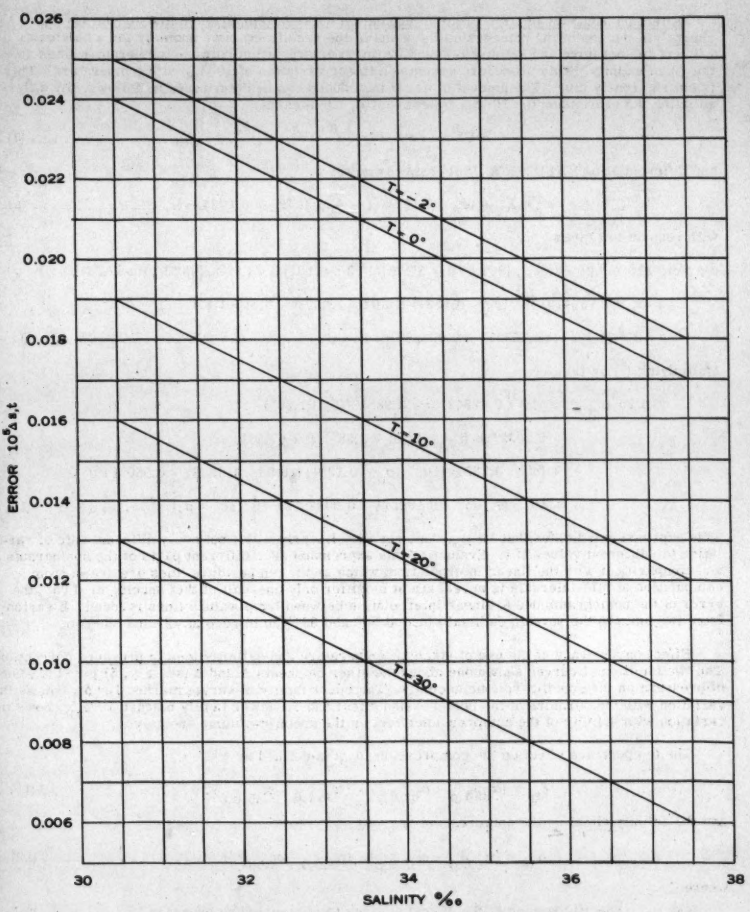


Fig. 4--Error due to use of straight temperature lines

may be secured. This is a measure of the precision of the nomograms resulting from the use of straight temperature lines in place of the actual curve.

Figure 4 shows the amount of this error for different values of temperature and salinity. The maximum departure (error) occurs at the lowest values of salinity and of temperature. For the same temperature the error decreases with increasing salinity, and for the same salinity it decreases with increasing temperature. The value of the maximum error is 0.025 and the minimum 0.006 unit in the fifth decimal place of specific-volume anomaly.

Effect on accuracy of first-order interpolation between temperature lines of the $10^5\Delta_{st}$ charts--In the use of the nomograms the value of the specific-volume anomaly for a particular value of temperature and salinity is found by linear interpolation between temperature lines at the given salinity. This procedure assumes a linear variation of $10^5\Delta_{st}$ with temperature. This is not rigorously true. The amount of error introduced can be determined as follows. By differentiating the expression for $10^5\Delta_{st}$ in terms of σ_t one obtains

$$d\,10^5\Delta_{st}/d\,\sigma_t = -10^8/(10^3+\sigma_t)^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots (7)$$

and differentiating KNUDSEN'S [1901] expression for σ_t

$$\sigma_t = \Sigma_t + (\sigma_o + 0.1324)[1 - A_t + B_t(\sigma_o - 0.1324\,B_t)] \quad \ldots\ldots\ldots\ldots\ldots\ldots (8)$$

with respect to t gives

$$d\,\sigma_t/dt = 215.74°\,(t° - 3.98)^2/[503.57\,(t+67.26)^2] - 2(t+283°)\,(t-3.96°)/[503.57\,(t+67.26)]$$
$$+(\sigma_o + 0.1324)\,[10^{-6}\,(\sigma_o - 0.1324)\,(18.03 - 1.6228t + 0.05001\,t^2)$$
$$- 10^{-3}\,(4.7867 - 0.19637t - 0.003252)] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

Multiplying (7) by (9) gives

$$d\,10^5\Delta_{st}/dt = -10^8\{0.428421\,(t-3.98°)^2/(t+67.26°)^2$$
$$- 0.0039716\,(t+283°)\,(t-3.98°)/(t+67.26)$$
$$+(\sigma_o + 0.1324)\,[10^{-6}\,(\sigma_o - 0.1324)\,(18.03 - 1.6328t + 0.05001\,t^2)$$
$$- 10^{-3}\,(4.7867 - 0.19637t + 0.0032529\,t^2)]\}/(10^3+\sigma_t)^2 \quad \ldots\ldots\ldots\ldots (10)$$

This expression indicates that $10^5\Delta_{st}$ does not vary linearly with t but has a different rate of variation for different values of t. Evaluating this expression over different parts of the nomograms and comparing it with the linear interpolation, which as the temperature lines are drawn from computation at 0.1° intervals is necessary at most for only one-half of this spacing or 0.05°, the error of the nomograms due to linear interpolation between temperature lines is found. It varies from two units in the seventh decimal place at 30° and 30 °/oo to zero at -2° and 38 °/oo.

Effect on accuracy of the use of straight temperature and salinity lines in pressure correction--The two families of curves shown one above the other on sheets A and B (see Fig. 5) give the effect of pressure on the specific-volume anomaly. The upper family of curves marked $10^5\,\delta_{tp}$ shows the variation with temperature of the compression effect and the lower family marked $10^5\delta_{sp}$ shows the variation with salinity of the compression effect on the specific-volume anomaly.

The temperature effect on the compression (δ_{tp}) is defined by

$$\delta_{tp} = (\alpha_{35,t,p} - \alpha_{35,0,p}) - (\alpha_{35,t,0} - \alpha_{35,0,0}) \quad \ldots\ldots\ldots\ldots\ldots\ldots (11)$$

and the salinity effect on the compression (δ_{sp}) by

$$\delta_{sp} = (\alpha_{s,0,p} - \alpha_{35,0,p}) - (\alpha_{s,0,0} - \alpha_{35,0,0}) \quad \ldots\ldots\ldots\ldots\ldots\ldots (12)$$

where

$\alpha_{35,t,p}$ = specific volume at S = 35 and at given temperature and pressure
$\alpha_{35,0,p}$ = specific volume at S = 35 t = 0 at given pressure
$\alpha_{35,t,0}$ = specific volume at S = 35 at given temperature and zero pressure
$\alpha_{35,0,0}$ = specific volume at S = 35 t = 0 and p = 0
$\alpha_{s,0,p}$ = specific volume at given salinity t = 0 and given pressure
$\alpha_{s,0,0}$ = specific volume at given salinity t = 0 and p = 0

The values of δ_{tp} and δ_{sp} are found by substituting the necessary values of α found from Ekman's mean compressibility equation

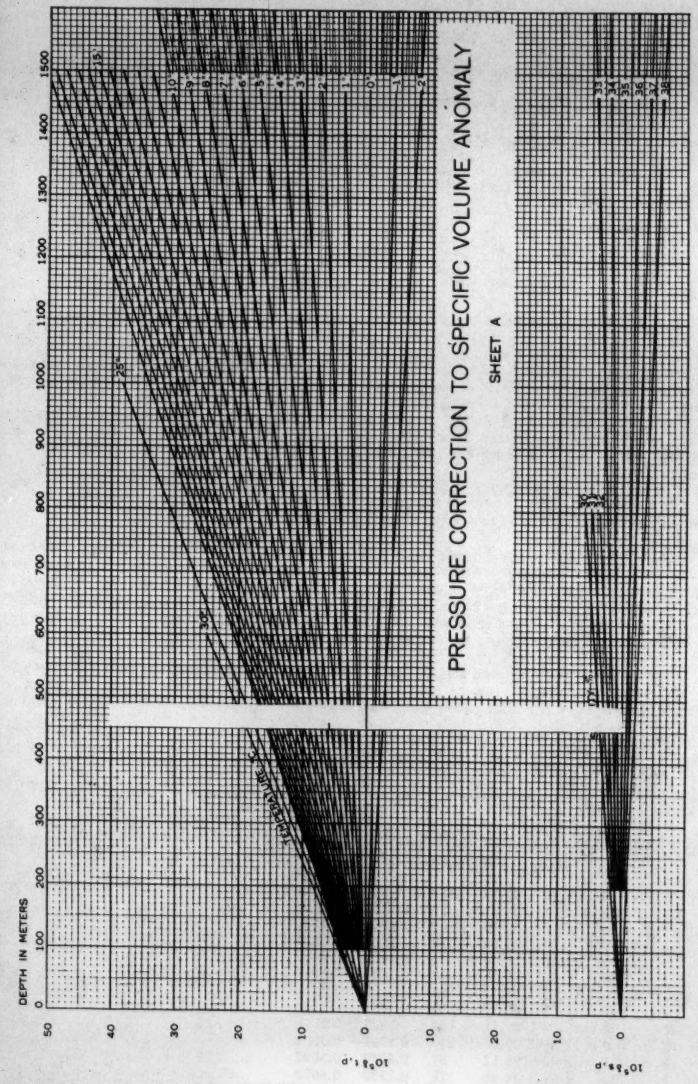


Fig. 5--Finding pressure correction

$$\alpha_{s,t,p} = \alpha_{s,t,0} - p\,\alpha_{s,t,0} \times 10^{-9}\Big\{4886/(1 + 0.0000183\,p) - [227 + 28.33t - 0.551t^2 + 0.004t^3 + p \times 10^{-4}\,[105.5 + 9.5t - 0.158t^2] - 1.5\,p^2 t\,10^{-8} - (\sigma_{s,0,0} - 28)/10\,[147.3 - 2.72t + 0.04t^2 - p \times 10^{-4}\,(32.4 - 0.87t + 0.002t^2)] + (\sigma_{s,0,0} - 28)^2/100\,[4.5 + 0.1t - p\,10^{-4}\,(1.8 - 0.06t)]\Big\} \quad (13)$$

where p = decibars; $\alpha_{35,0,0} = 28.13$; and $\alpha_{35,0,0} = 0.97264$

The temperature lines of the pressure-correction section of the nomograms ($10^5\delta_{tp}$) are drawn as chords connecting the following points of pressure (depth)

0	50	250	700	2000
10	75	300	800	2500
20	100	400	1000	3000
25	150	500	1200	4000
30	200	600	1500	5000

The departure of the actual curve from these chords at their midpoints can be found by comparing the computed and interpolated values at the midpoints of the chords, using (11) and (13). By use of these values over the nomograms the maximum departure of the temperature lines of the pressure correction is found to be one unit in the sixth decimal place of $10^5\delta_{tp}$. By taking the second derivative of $10^5\delta_{tp}$ with respect to pressure ($d^2 10^5\delta_{tp}/dp^2$) the curvature of the temperature lines of the pressure correction may be found. In the case of the 10° line: $d^2 10^5\delta_{tp}/dp^2 = -0.000196/(1 + 0.0000183\,p)^3 - 10^{-4} \times 154.3 + 10^{-8} \times 87.66\,p$ which is negative for all values of p (depth) shown on the nomogram. This means that the curve is concave from below and the value, computed minus interpolated $10^5\delta_{tp}$, is positive.

Use of straight salinity lines in pressure correction--In similar fashion the maximum departure of the actual salinity lines of the pressure correction from the straight line chords at their midpoints is found to be two in the seventh place of $10^5\delta_{sp}$.

Linear interpolation between temperature lines of the pressure correction--In the use of the nomograms it is necessary to interpolate for the given temperature between the temperature lines shown. The variation of $10^5\delta_{tp}$ with temperature is not exactly linear. The amount of difference between linear (first order) interpolation and the actual value of $10^5\delta_{tp}$ at the point can be found by comparing the interpolated value with the value computed by (11) and (13). The maximum difference is found to be one unit in the seventh place of $10^5\delta_{tp}$.

Linear interpolation between salinity lines of the pressure correction--In the same manner the maximum difference between the interpolated and computed values of $10^5\delta_{sp}$ for the given salinity is found to be less than one in the sixth place of $10^5\delta_{sp}$, found by the use of (12) and (13).

Use of the nomograms--The use of the nomograms can be shown by reducing the data from two stations in the North Atlantic south of the Grand Banks for the purpose of determining the current component normal to a section joining the two stations (see Table 2).

Table 2--Sample current computation

Station	m	T	S	$10^5\delta$	ΔD	ΔD	$\Delta D_2 - \Delta D_1$	Rel. current	
	1	2	3	4	5	6	7	8a	8b
						dyn m		cm/sec	cm/sec
1	0	5.72	33.93	129	.....	.....	.....	.....	63
1	50	12.01	35.31	122	0.0627	0.0627	0.0265	4.6	59
1	125	10.13	35.16	103	0.0844	0.1471	0.0647	11.4	52
1	250	6.72	35.00	65	0.1050	0.2521	0.1341	23.6	40
1	450	5.40	35.04	48	0.1130	0.3651	0.2441	42.9	20
1	750	4.81	35.01	47	0.1425	0.5076	0.3596	63.2	0
2	0	18.12	36.21	183	.....	.....	.....	.....	...
2	50	18.01	36.33	174	0.0892	0.0892	.....	.....	...
2	125	16.33	36.11	153	0.1226	0.2118	.....	.....	...
2	250	12.91	35.56	126	0.1744	0.3862	.....	.....	...
2	450	9.22	35.12	97	0.2230	0.6092	.....	.....	...
2	750	6.61	34.95	75	0.2580	0.8672	.....	.....	...

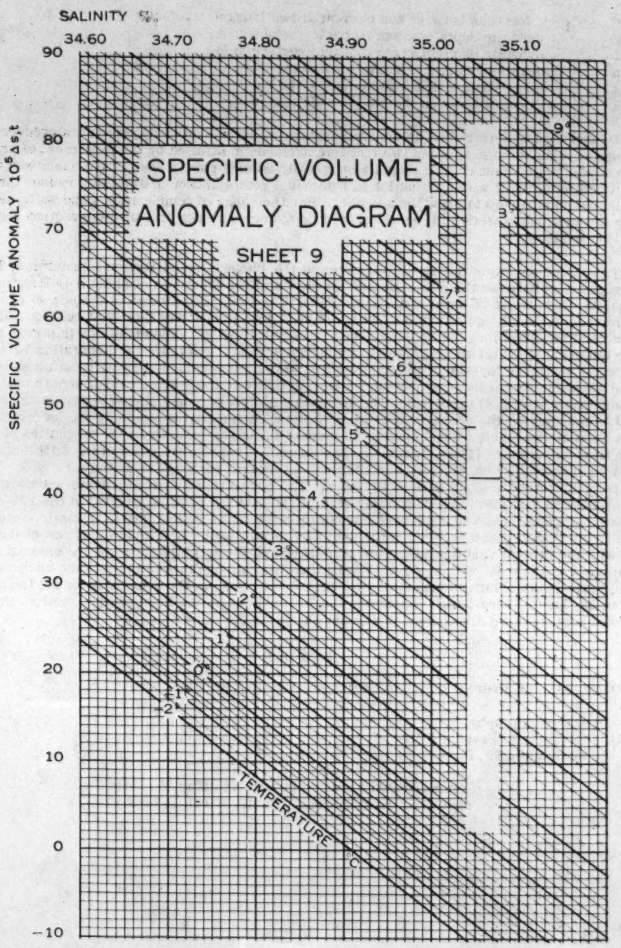


Fig. 6--Finding $10^5\Delta_{st}$ value

It is convenient to use the formula for which the current computation nomogram is designed, namely

$$C_o - C_1 = (D_a - D_b)/2\omega \sin \phi_m L \quad \ldots\ldots\ldots\ldots\ldots\ldots (14)$$

where

$C_0 - C_1$ = difference between the current at two isobaric surfaces
D_a = dynamic depth of given isobaric surface at A
D_b = dynamic depth of given isobaric surface at B
ω = angular velocity of Earth's rotation
ϕ_m = mean latitude of the stations (41° 10′)
L = distance between the stations (32 naut mi)

D_a and D_b are determined by the temperature-salinity-depth data, being the product of the average specific volume between two isobaric surfaces multiplied by the increment of pressure between the two surfaces. The anomaly of specific volume can be used in the same way as the specific volume itself with a reduction in numerical complication, and for this reason the nomograms are constructed to show the anomaly. For the range of temperatures and salinities at these two stations, sheets 6, 9, and 11 (Fig. 1), together with the pressure correction sheet A (Fig. 5), are needed.

To extract the value for the $10^5\delta$ column at the 450-m level at Station 1 (column 4, Table 2): The separation between the index lines of the two families of curves of sheet A is first marked on a straight edge (a slip of paper will do) (Fig. 5). The lower left corner of the slip of paper is then placed upon the depth-salinity point 450 m, 35.04 °/oo, in the lower family of curves. With the left edge of the slip along the 450-m depth line, a pencil mark is then made on this edge at the depth temperature point 450 m, 5.40° in the upper family of curves. The separation between the two pencil marks on the slip of paper is applied to the temperature-salinity point on sheet 9 (Fig. 6) and the value 48 read on the ordinate scale. In this way the entries for all depths in the $10^5\delta$ column (Table 2, col. 4) are made. The anomalies of dynamic depth between levels are next found by multiplying the average value of $10^5\delta$ between respective levels by the increment of depth between the levels. The cumulative sums of these are entered as the anomalies of dynamic depth from the surface (Table 2, col. 5). In column 7, Table 2, are entered the differences between the dynamic-depth anomalies of respective isobaric surfaces at Stations 1 and 2. The current computation nomogram is used to find the current from the dynamic-depth anomaly difference in column 7, Table 2. For example (Fig. 2), to find the relative current at the 125-m level, a straight edge is placed to connect the dynamic-depth difference of 0.0647 dynamic meters, scale 1, to the difference between stations of 32 naut mi, scale 2. The intersection of the straight edge with the central vertical index line is marked and the straight edge used to connect this point to the mean latitude 41° 10′, scale 4. Where the straight edge now intersects the current velocity scale, scale 3, the relative current of 11.4 cm/sec is read. In the same manner all the entries in column 8a, Table 2, are found. Assuming the 750-m level as the level of zero motion, the currents from the surface down are written in column 8b, Table 2.

Reference

KNUDSEN, Martin, Hydrographic tables, 63 pp., Copenhagen, 1901.

Division of Oceanography,
U. S. Navy Hydrographic Office,
Washington 25, D. C.

(Communicated manuscript received May 31, 1950;
open for formal discussion until March 1, 1952.)

Transactions, American Geophysical Union Volume 32, Number 5 October 1951

TERRESTRIAL HEAT FLOW IN ONTARIO AND QUEBEC

A. D. Misener, L. G. D. Thompson, and R. J. Uffen

Abstract--From some 1000 measurements of true rock temperatures, correct to 0.1°F, made at various depths in eight regions of Ontario and Quebec, average vertical temperature gradients for each location were obtained. Thermal conductivity measurements involving the preparation of approximately 300 rock specimens collected near the points of temperature measurement were carried out using the divided-bar method. The terrestrial heat flow was computed for each region. The values obtained lie between 0.69×10^{-6} and 1.05×10^{-6} cal/cm^2/sec. Statistical analysis and rejection criteria were employed to determine the best values and probable errors of the calculated heat flows. It was found that the variations in heat flow for the various regions were greater than the probable errors, the regions having the higher temperature gradients also having the greater heat flow. Broadly speaking, the regions of greater heat flow are located in the Grenville geological sub-province while those with the lower are in the Superior sub-province.

Introduction--Investigations into the amount of heat flowing to the surface of the Earth from its interior have been conducted for many years. However, reliable determinations of this important geophysical quantity have been determined in only a few locations and the complete understanding of the thermal history of the Earth awaits the accumulation of additional accurate data. It was felt that the techniques previously employed for these determinations elsewhere in the world could be improved and that present knowledge would be significantly supplemented by making use of the unique facilities present in the well-developed mining regions of Ontario and Quebec.

The determination of the terrestrial heat flow requires the measurement of two separate quantities: the temperature gradient existing at a location and the thermal conductivity of the rocks in which the temperature gradient is measured.

Early estimates were based upon conductivities and gradients not necessarily measured at the same place and lead to uncertain values, since shown to be high [JEFFREYS, 1929]. Careful measurements of temperature gradients in deep bore holes and of the thermal conductivity of rocks taken at various depths from the same bore holes have provided more reliable values [BENFIELD, 1939; BULLARD, 1939]. Further, this method permits the study of regional variations. However, it was felt that the practice of determining heat flow from the temperatures and conductivities obtained in a few vertical bore holes might give results divergent from the average for a particular region.

The procedure followed in this investigation was to select locations where mine workings extended to a considerable depth over a reasonably wide area. The mean gradient and rock conductivities were obtained for each location and the heat flow was computed.

Temperature measurements--At selected depths below surface, horizontal drill holes extending into regions of undisturbed rock were located. Platinum resistance thermometers and, later, thermistor resistance thermometers were inserted into these holes far enough to record the true rock temperature.

The platinum resistance thermometers were calibrated at the ice-point at the freezing point of mercury, and at the sublimation point of carbon dioxide. A Cambridge dial potentiometer was used to measure the resistance during the preliminary work. Later measurements were made with a standard Kelvin double-bridge and a Leeds and Northrup box galvanometer. The thermistor resistance thermometers were calibrated against a standard platinum resistance thermometer. The bridge used with these thermometers was one of a number designed and built by the Meteorological Division of the Department of Transport. Thermistor resistance thermometers have the practical advantage of high resistance combined with a very large negative temperature coefficient of resistance.

To ensure that true rock temperatures were being measured, many of the holes were

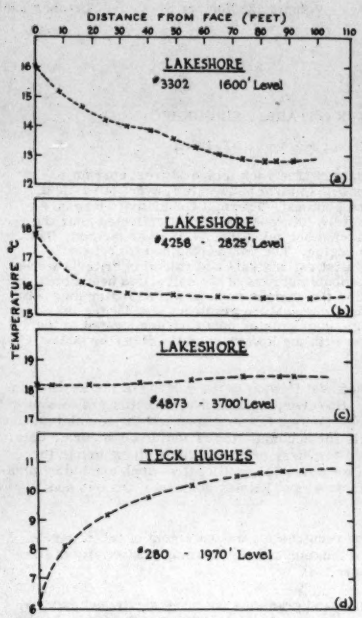


Fig. 1--Variation of temperature with distance from collar in horizontal underground drill holes

"logged" to discover how far the effects of ventilation extended. It was found that if measurements were taken 70 feet from the rock face no effects due to ventilation were apparent (see Fig. 1 and other examples) [MISENER, 1949, Fig. 1]. Care was taken to allow sufficient time to elapse, after drilling, for the rock to reach temperature equilibrium to within 0.1°F before the measurements were made. For long drill holes this time may be considerable [BULLARD, 1947]. An example of the time variation of temperature for a short drill hole (10 feet) is shown in Figure 2. The equilibrium temperatures were measured in an old drill hole (no. 2489) situated two feet from the new drill hole.

From the many temperature measurements throughout a given region graphs were made showing the variation of temperature in three dimensions. From these, isothermal levels were calculated by interpolation. These were not planes parallel to the surface but showed marked anomalies which strengthened our opinion that a single vertical gradient might well diverge from the average for the region (see Fig. 3). The average vertical temperature gradient was determined from the regional isothermal levels. The temperature gradients are of practical interest to the mining industry and therefore the details of technique and results obtained have been previously published [MISENER, 1949; MISENER and THOMPSON, 1950]. The average temperature gradients are here reproduced in Figure 4.

Thermal conductivity measurements--Thermal conductivity measurements of rock specimens prepared from samples collected near the points of temperature measurements were carried out using the divided-bar method. In this method, a disc-like specimen is placed between two vertical cylindrical brass bars and heat is supplied at the upper end by an electric heater and abstracted at the bottom by the circulation of cold water. The temperatures at a number of points in the brass bars are measured by thermojunctions and the ratio of the temperature gradient in the brass to that in the specimen is determined. Three specimens, of different thickness, of each rock sample are measured. The apparatus was that used by Bullard and is one of three that have been calibrated by standardization with the same specimens of crystalline quartz

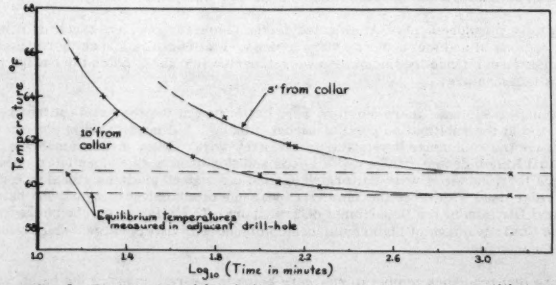


Fig. 2--Time required for drill hole to reach temperature equilibrium

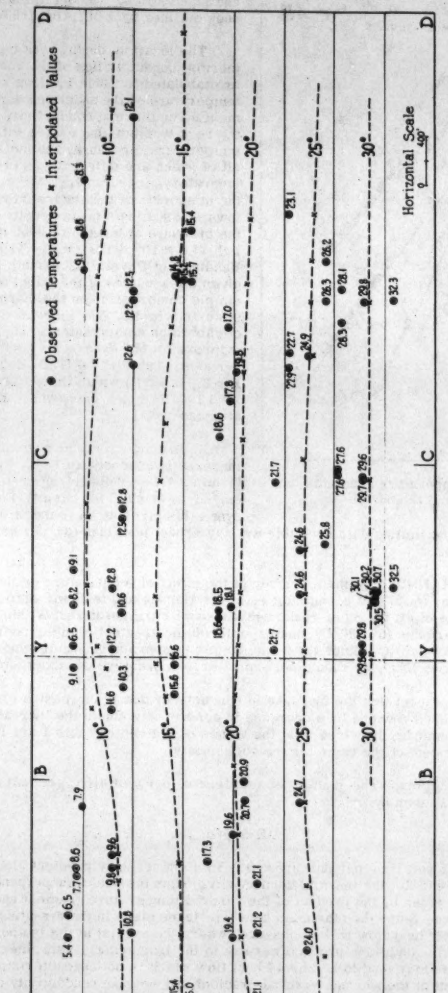


Fig. 3--Variation of isothermal levels in a typical region (Kirkland Lake area, projection on X-X')

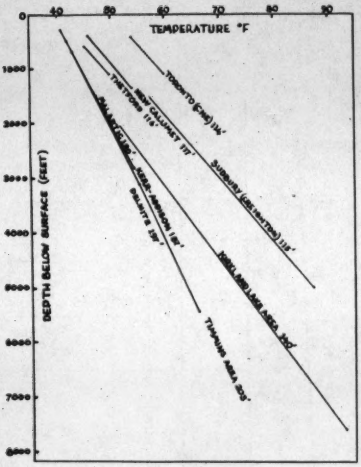


Fig. 4--Average temperature gradients in Ontario and Quebec

and fused silica. The details of the method have been outlined by BULLARD [1939].

The location, depth, rock type, density, and thermal conductivities of the rock specimens are tabulated in Table 1, along with the mean temperature of the specimen during measurement. The thermal conductivity (K) depends on the rock type but also varies with changes of temperature, pressure, and moisture content, all of which are different in situ than in the laboratory measurement. We therefore estimate the magnitude of the errors introduced as follows: Assuming a mean density of 2.7 gm/cc, the pressure at a depth of 3000 m is $p = \rho g h \approx 8 \times 10^8$ dynes/cm^2. Table 17-41 of the Handbook of Physical Constants [BIRCH, 1942] gives a few values of the effect of wetting and simple compression on the thermal conductivity of certain rocks. The increase in conductivity of gabbro on compression to 10,000 lb/in.^{2} (approx. 7×10^8 dynes/cm^2) is given as two per cent. Table 17-10 [BIRCH, 1942] gives $K = K_0 (1 + \alpha P)$ within the pressure range $1 - 12 \times 10^9$ dynes/cm^2, where K is conductivity at pressure P.

K_0 is conductivity at normal pressure. The increase in conductivity $K/K_0 = \alpha P$, and α is given as 4.7×10^{-6} cm^2/kg or $\alpha = 4.7 \times 10^{-12}$ cm^2/dyne at 30°C for basalt. For $P = 8 \times 10^8$ dynes this gives an increase of 0.4 pct in conductivity. Thus, with the limited data available we may expect less than two per cent error in K for our deepest samples.

BIRCH and CLARK [1940] have made a study of the effect of temperature on the thermal conductivity of rocks. They found that conductivities of the glasses and feldspar aggregates increased with temperature; those of all the other rocks decreased with temperature. Within the temperature range which concerns us (0 - 30°C), quartz suffered the greatest change, having a decrease in conductivity of 0.4 pct per °C. Since the mean sample temperatures of our specimens, during measurement, were about 20°C, we should not expect errors greater than about four per cent.

It is reasonable to expect that the increase in conductivity due to increasing pressure with depth will be in most cases reduced by a decrease in conductivity due to the increase of temperature with depth. We conclude, therefore, that the values of K given in Table 1 are likely to be within two or three per cent of the value for the rock in situ.

Heat-flow determinations--The quantity of heat flowing per unit area, per unit time, across any surface in a body is given by

$$H = - K \partial T/\partial n \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where H = heat flow per unit time per unit area, $\partial T/\partial n$ = temperature gradient along the outward normal to the surface, and K = the thermal conductivity. Thus the heat flow perpendicular to the surface of the Earth is given by the product of the vertical temperature gradient and the thermal conductivity of the rocks. Since the maximum heat flow takes place in the direction normal to the isothermals, the greatest heat flow will be observed where the normal to the isothermals is vertical. If local geologic conditions produce warping in the isothermal levels, measurements in a single vertical bore hole may lead to a value of heat flow which is not characteristic of that locality. Thus the product of the average vertical gradient and average conductivity of the rocks for any locality should provide a more representative value of heat flow for that locality.

To determine the average conductivity of the rocks would require a large number of samples and the weighting of the results according to the amounts of the different rock types present. This was not practicable, so the technique employed was to multiply the average gradient by the conductivity of samples taken at different depths and then find the "best value" of the heat flow by the

Table 1--Thermal conductivity of rocks

Location	Sample	Depth	Rock type	Thermal conductivity K $\times 10^4$	Mean temperature	Density
		ft		cgs units	°C	gm/cm^3
Lake Shore Mine, Kirkland Lake, Ontario	LS 3250	800	Syenite porphyry	75.7	20	2.72
	LS 4325	800	Syenite porphyry	74.3	21	2.70
	LS 3958	800	Syenite porphyry	75.2	19	2.71
	LS 2489 SP	1600	Syenite porphyry	74.5	22	2.70
	LS 4931	1600	Syenite porphyry	64.0	18	2.71
	LS 3193	1800	Syenite porphyry	71.4	21	2.68
	LS 2870	1800	Syenite porphyry	77.7	20	2.53
	LS 4359	2825	Augite syenite	67.0	20	2.69
	LS 1716	3950	Syenite porphyry (silicified)	73.7	19	2.73
	LS 4338	4200	Syenite porphyry (silicified)	79.9	18	2.70
	LS 4274	4200	Syenite porphyry (silicified)	143.3	17	2.66
	LS 3206	4825	Syenite porphyry	94.8	18	2.69
	LS 3588	4825	Syenite porphyry	71.5	20	2.67
	LS 5327	5075	Syenite porphyry	74.3	18	2.72
	LS 4815	5825	Syenite porphyry (sheared)	78.2	19	2.72
	LS 5326	6075	Syenite porphyry (sheared)	67.8	16	2.75
	LS 4257	6825	Syenite porphyry	85.0	19	2.69
	LS 5237	6893	Syenite porphyry	80.3	18	2.68
Teck-Hughes Mine, Kirkland Lake, Ontario	TH 2300	728	Syenite	75.4	16	2.78
	TH 2969	857	Syenite porphyry	63.2	25	2.69
	TH 3000	977	Syenite	75.4	21	2.69
	TH 2993	1605	Syenite porphyry	86.1	22	2.69
	TH 280	1981	Lamprophyr	82.2	20	2.76
	TH 3177	3978	Syenite porphyry	80.7	22	2.73
	TH 2602	3978	Syenite porphyry	80.2	17	2.80
	TH 1183	4477	Syenite porphyry	78.0	22	2.69
	TH 2667	4477	Syenite porphyry	76.9	17	2.68
	TH 2633	4477	Syenite porphyry	77.5	17	2.67
	TH 1629	5476	Syenite porphyry	95.0	22	2.67
Wright Hargreaves Mine, Kirkland Lake, Ontario	WH 236	2000	Syenite porphyry	75.1	21	2.72
	WH 2787	2850	Syenite porphyry	76.0	18	2.70
	WH 3607	3000	Syenite porphyry	75.5	17	2.68
	WH ?	4050	Syenite porphyry	84.0	16	2.70
	WH 1451	5100	Syenite porphyry	77.0	20	2.69
	WH 3454	5100	Syenite porphyry	82.1	22	2.68
	WH 2448	5100	Syenite porphyry	78.8	19	2.72
	WH 1402	5500	Syenite porphyry	74.5	18	2.75
	WH 1327	5850	Syenite porphyry	69.3	16	2.70
	Test Hole	6600	Syenite porphyry	74.9	17	2.67
	WH 3631	7200	Syenite porphyry	73.7	19	2.70
McIntyre Mine, Timmins, Ontario	McI 5211	1250	Altered rhyolite	96.9	16	2.90
	McI ?	5100	Quartz sericite schist	82.8	16	2.83
	McI ?	4100	Schist	63.6	24	2.71
Delnite Mine, Timmins, Ontario	Del. 750	300	Rhyolite breccia	73.9	16	2.82
	Del. 757	1000	Rhyolite	75.2	15	2.85
	Del. 885	1250	Rhyolite	80.4	16	2.81
	Del. 1183	1500	Mineralized rhyolite breccia	78.8	16	2.90

(Continued)

Table 1--Thermal conductivity of rocks (concluded)

Location	Sample	Depth	Rock type	Thermal conductivity K $\times 10^4$	Mean temperature	Density
		ft		cgs units	°C	gm/cm^3
Delnite Mine, Timmins, Ontario--Concluded	Del. 394	1500	Altered ryolite	80.0	17	2.82
	Del. 1185	1750	Quartz breccia[a]	162.4	14	2.69
	Del. 1247	2750	Metamorphosed rhyolite	87.6	16	2.84
King Mine, Thetford Mines, Quebec	King 2A	900	Serpentinized peridotite	56.9	17	2.63
	King 2B	900	Serpentinized peridotite	62.1	16	2.64
	King 2C	900	Serpentinized peridotite	63.9	17	2.63
	King 3A	900	Serpentinized peridotite	70.1	15	2.60
	King 5A	900	Serpentinized peridotite	64.1	17	2.58
	King 6	900	White serpentine	62.7	17	2.71
	King 1A	900	Serpentine altered to brucite	77.0	24	2.80
	King 1B	900	Serpentine altered to brucite	75.0	25	2.76
New Calumet Mine, Calumet Island, Quebec	N.C. 7-8	750	Quartz diorite	50.3	18	2.68
	N.C. 10-8	1050	Metamorphosed quartz gabbro	156.0	21	2.71
	N.C. 13-2	1350	Hornblende gabbro	66.2	18	3.08
	N.C. 13-3	1350	Amphibole schist	65.7	17	3.15
Creighton Mine, Sudbury, Ontario	CR 6322	1075	Norite	70.5	18	2.88
	CR 5100	2000	Norite	64.7	19	2.75
	CR 2132	3000	Norite	55.2	17	3.00
	CR 7288	4050	Norite	58.0	19	3.05
C.N.E. Oil Well, Toronto, Ontario	Ex 568	568	Limestone	43.5	21	2.68
	Ex 575	575	Limestone	59.3	23	2.67
	Ex 794	794	Limestone	61.7	18	2.70
	Ex 796	796	Limestone	65.7	19	2.72
	Ex 890	890	Limestone	62.2	20	2.71
	Ex 990	990	Limestone	71.1	16	2.71
Kerr-Addison Mine, Larder Lake, Ontario	Kerr 25-24	2500	Grey carbonate	70.8	24	2.89
	Kerr 25-61	2500	Grey flow	104.0	24	2.87
	Kerr 25-28	2500	Grey carboniferous tuff	95.5	25	2.88
	Kerr 25-11	2500	Black flow	83.9	24	2.91
	Kerr 25-82	2500	Brown carbonate	92.6	24	2.96
	Kerr 25-78	2500	Green carbonate	98.1	25	2.92
Creighton Mine, Sudbury, Ontario	CR L40	2600	Mineralized norite	66.9	24	3.09
	CR L62	4800	Norite	72.5	22	2.67
Malartic Gold Fields, Malartic, Quebec	Mal. 1	300	Diorite	70.9	21	2.91
	Mal. 3	300	Silicified schist	60.4	24	2.88
	Mal. 27	600	Chlorite schist	64.2	24	2.87
	Mal. 9	750	Chlorite schist	67.1	24	2.88
	Mal. 29	900	Silicified diorite	78.8	23	2.92
	Mal. 20	1200	Silicified chlorite schist	114.0	21	2.87
	Mal. 22	1200	Amphibolite	64.7	23	2.97
	Mal. 31	1200	Diorite	54.7	23	2.82
	Mal. 34	1500	Green schist	81.7	19	2.84

[a]Sample from region with abnormally high gradient.

Table 2--Sample computation of heat flow, C.N.E. Oil Well, Toronto, Ontario
(Average temperature gradient, $G = 16.0 \times 10^{-5}$ °C/cm; best value of heat flow, $H = (1.03 \pm 0.05) \times 10^{-6}$ cal/cm^2/sec)

Sample	Depth	Thermal conductivity G $\times 10^4$	First evaluation: Heat flow $\times 10^6$	$v \times 10^6$	$v^2 \times 10^{12}$	Chauvenet's criterion: n	ℓ	$\ell p \times 10^6$
	ft	cgs units	cal/cm^2/sec					
Ex 568	568	46.5	0.745	0.234	0.0547	6	2.57	0.232
Ex 575	575	59.3	0.950	0.029	0.0008	Reject Ex 568		
Ex 794	794	61.7	0.987	0.008	0.0001			
Ex 796	796	65.7	1.050	0.071	0.0050			
Ex 890	890	62.2	0.995	0.016	0.0003			
Ex 990	990	71.1	1.149	0.170	0.0289			
			6 | 5.876	$\Sigma v^2 = 0.0898$				
			0.979	$p = 0.675\sqrt{0.0898/5}$				
				$= 0.0903 \times 10^{-6}$				
			Second evaluation					
Ex 568	568	46.5	.....	.....	.....	5	0.244	0.127
Ex 575	575	59.3	0.950	0.076	0.0058	No rejects		
Ex 794	794	61.7	0.987	0.039	0.0015			
Ex 796	796	65.7	1.050	0.024	0.0006			
Ex 890	890	62.2	0.995	0.031	0.0010			
Ex 990	990	71.1	1.149	0.123	0.0151			
			5 | 5.131	$\Sigma v^2 = 0.0240$				
			1.026	$p = 0.675\sqrt{0.0240/4}$				
				$= 0.0522$				

Table 3--Summary of heat-flow computations

Region	Mine	Average temperature gradient $\times 10^5$	Heat flow $\times 10^6$: Before rejection, Rate	Before rejection, Probable error	After rejection, Rate	After rejection, Probable error
		°C/cm	cal/cm^2/sec	pct	cal/cm^2/sec	pct
Toronto	C.N.E. Oil Well	16.0	0.98	9	1.03	5
Sudbury	Creighton	15.8	1.01	6	1.01	6
Thetford	King	15.7	1.05	7	1.05	7
Calumet Island	New Calumet	15.6	1.32	39	1.32	39
Kirkland Lake	Lake Shore	13.0	1.04	15	0.97	5
	Teck-Hughes	13.0	1.03	7	1.03	3
	Wright-Hargreaves	13.0	0.99	4	0.99	4
Malartic	Malartic Gold Fields	10.1	0.77	17	0.89	7
Larder Lake	Kerr-Addison	9.74	0.88	9	0.88	9
Timmins	Delnite	9.24	0.79	14	0.73	4
	McIntyre	8.96	0.73	14	0.73	14

application of Chauvenet's criterion of rejection [TUTTLE and SATTERLY, 1925, chap. 17].

In any localized region of the Earth's crust it is reasonable to assume that the heat flow to the surface is constant throughout the region although the region may be composed of a variety of rocks of different conductivities. If the inhomogeneities are large enough, they will produce warping of the lines of heat flow away from the vertical and result in warping of the isothermal levels from the horizontal. However, a reliable average vertical temperature gradient may be determined as described above. For any small rock sample within the region the temperature gradient in the sample will be inversely proportional to the conductivity of the rock. These local variations in gradient are all smoothed out in the average gradient for the region. If we happen to have taken a rock sample whose conductivity is widely divergent from the weighted mean conductivity of the region and multiply its conductivity by the average gradient, we will get a value of heat flow that is widely divergent from the average heat flow.

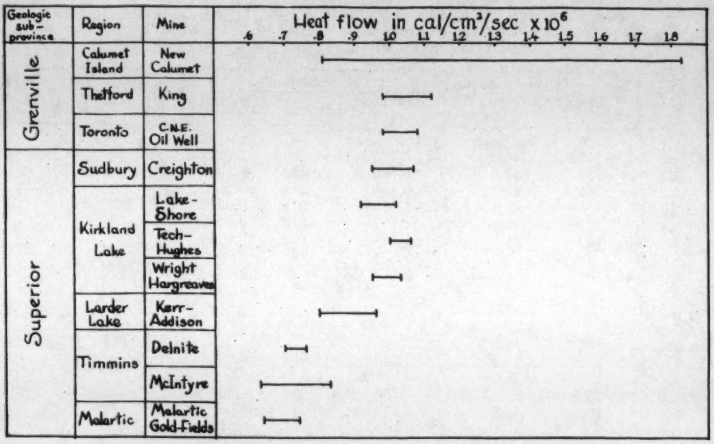


Fig. 5--Variation of heat flow in the various regions; the lengths of the lines indicate the magnitude of the probable error

The use of Chauvenet's criterion is an attempt to reject divergent values without resorting to arbitrary judgments. For those unfamiliar with the particular criterion of rejection we have used, a brief outline of it is given in Appendix 1.

A sample of the computations of heat flow is shown in Table 2 and the summarized results are shown in Table 3. Since the number of determinations for some locations is small, the probable errors stated should be treated with caution. New Calumet Mine, for which only four conductivity measurements were obtained (one of which was much different from the others), illustrates this point.

Discussion--The heat flows obtained fall in the range 0.73×10^{-6} to 1.05×10^{-6} cal/cm^2/sec. These are in good agreement with those obtained by BENFIELD [1939] in Great Britain, BULLARD [1939] in South Africa, and COSTER [1947] in Persia, but are significantly lower than that obtained by BIRCH [1950] in the Front Range, Colorado. Birch has shown that this higher value can be accounted for in terms of mountain roots having a mean radioactivity of the same order as that of granites or intermediate rocks.

With due regard for the probable errors, an examination of the gradients (Fig. 4) and heat flows of Table 3 and Figure 5 suggests that the regional variations are not accidental. In general, the regions with steeper gradients have the greater heat flow and are located in the Grenville subprovince with the exception of Kirkland Lake [WILSON, 1949]. Recent gravity observations in Ontario have indicated warpings at the base of the granitic and intermediate layers of the Earth's crust which have been interpreted as remanental roots of Pre-Cambrian mountain systems [GARLAND, 1950; UFFEN, 1950], the thickness of the granitic layer varying between 14 and 22 km.

If we assume a difference in the rate of radioactive heat production between granitic and basaltic rocks of 3 to 4×10^{-3} cal/cm^3/sec [BIRCH, 1942], a difference in thickness of the granitic layer of seven to ten km would produce a difference in heat flow at the surface of 0.3×10^{-6} cal/cm^2/sec. Thus the observed regional variation of heat flow can be reasonably attributed to warpings at the base of the granitic layer.

It will be noted that we have made no attempt to apply any "ice-age corrections" to the observed gradients or the heat-flow values. Neither have we attempted to "correct" for the erosion of the surface. These phenomena have undoubtedly affected the temperature gradients but the magnitude of their effect can be calculated with validity only if there is an observable variation of gradient with depth which can not be reasonably attributed to other causes. In any one region the

values of temperature down a vertical line would show variations in gradient but over the whole region these variations were widely different and could hardly, therefore, be attributed to the thermal history of the surface. It seems much more probable that they are caused by local variations of conductivity. Reference to Table 1 gives ample proof of wide variation of conductivity among samples of the same rock type. We therefore feel that in this investigation there is no justification for attempting such "corrections" to the heat-flow values.

Acknowledgments--The Research Council of Ontario has provided all the funds needed to carry out the work during its entire course. In addition, members of the Council have aided us by their encouragement and by establishing cordial relations with the mining industry.

These results could only be obtained through the courtesy and cooperation of the personnel in the mines visited. We are grateful to the managers, the geologists, and the engineers for assisting in the considerable transportation of men and equipment underground and for permitting the dislocation of their schedules which our work inevitably caused. Since a personnel list would be far too lengthy, we express our thanks formally to their companies: Asbestos Corporation, Ltd. (King Mine); Delnite Mines, Ltd.; Hollinger Consolidated Gold Mines, Ltd.; International Nickel Co. of Canada; Kerr Addison Gold Mines, Ltd.; Lake Shore Mines, Ltd.; Malartic Gold Fields, Ltd.; McIntyre Porcupine Mines, Ltd.; New Calumet Mines, Ltd.; Teck-Hughes Mines, Ltd.; Wright-Hargreaves Mines, Ltd.

Numerous students have, from time to time, carried out various portions of the measurements without the satisfaction of participating in the final outcome. We thank the following for their individual contributions to this work: G. W. Johnson, T. H. Leith, E. R. Niblett, P. O'Rourke, and D. T. Shaw.

We acknowledge our indebtedness to J. T. Wilson of the Geophysics Department, University of Toronto, for initiating the project as part of a plan for the intensive geophysical study of the Canadian Shield and for his continuing advice and encouragement.

APPENDIX 1--CHAUVENET'S CRITERION OF REJECTION

The object of a criterion of rejection is not to indicate that a certain measurement is wrong, but merely to point out that it is liable to be misleading if it occurs among a small group.

In a series of n measurements, no one measurement ought to have a deviation v greater than ℓp, where p is the probable error of an individual measurement and ℓ is defined as

$$\ell = x/y$$

where

$$(2/\sqrt{\pi})\int_0^x e^{-x^2}\,dx = (2n - 1)/2n$$

and

$$(2/\sqrt{\pi})\int_0^y e^{-y^2}\,dx = 1/2$$

The values of ℓ for different values of n are given in Table 4. Thus if the most divergent measurement of a series of n determinations has a deviation v more than ℓ times as great as the probable

Table 4--Chauvenet's criterion

n	ℓ	n	ℓ	n	ℓ	n	ℓ
1	1.00	11	2.97	21	3.35	32	3.59
2	1.71	12	3.02	22	3.38	34	3.62
3	2.05	13	3.07	23	3.40	36	3.65
4	2.27	14	3.11	24	3.43	38	3.68
5	2.44	15	3.15	25	3.45	40	3.70
6	2.57	16	3.19	26	3.47	49	3.81
7	2.67	17	3.22	27	3.49	64	3.95
8	2.76	18	3.26	28	3.51	81	4.06
9	2.84	19	3.29	29	3.53	100	4.16
10	2.91	20	3.32	30	3.55	671	5.00

error of the individual measurements, it may be rejected. If two or more such values are found, only the most divergent one may be rejected. A new average is found for those that remain and the criterion is applied to them in turn. A more complete discussion is given by TUTTLE and SATTERLY [1925].

References

BENFIELD, A. E., Terrestrial heat flow in Great Britain, Proc. R. Soc. London, v. 173, pp. 428-450, 1939.

BIRCH, F. (ed.), Handbook of physical constants, Geol. Soc. Amer., Spec. Paper 36, 325 pp., 1942.

BIRCH, F., Heat flow in the Front Range, Colorado, Bull. Geol. Soc. Amer., v. 61, pp. 567-630, 1950.

BIRCH, F., and H. CLARK, The thermal conductivity of rocks and its dependence upon temperature and composition, Amer. J. Science, v. 238, pp. 529-558, 613-635, 1940.

BULLARD, E. C., Heat flow in South Africa, Proc. R. Soc. London, ser. A, no. 955, v. 173, pp. 474-502, 1939.

BULLARD, E. C., The time necessary for a bore hole to attain temperature equilibrium, Mon. Not. R. Astron. Soc., Geophys. Sup., v. 5, pp. 127-130, 1947.

COSTER, H. P., Terrestrial heat flow in Persia, Mon. Not. R. Astron. Soc., Geophys. Sup., v. 5, pp. 131-146, 1947.

GARLAND, G. D., Interpretations of gravimetric and magnetic anomalies on transverses in the Canadian Shield in northern Ontario, Pub. Domin. Obs'y, Ottawa, v. 16, no. 1, 57 pp., 1950.

JEFFREYS, H., The Earth, Cambridge Univ. Press, 278 pp., 1929.

MISENER, A. D., Temperature gradients in the Canadian Shield, Can. Min. Metal. Bull., Trans., v. 52, pp. 125-132, 1949.

MISENER, A. D., and L. G. D. THOMPSON, Temperature gradients in Ontario and Quebec, Can. Min. Metal. Bull., Trans., v. 53, pp. 280-287, 1950.

TUTTLE, L., and J. SATTERLY, The theory of measurements, Longman's Green and Co., 333 pp., 1925.

UFFEN, R. J., Gravitational and geological study of the Grenville and Superior Provinces, unpublished thesis, Dept. of Physics, University of Toronto, 117 pp., 1950.

WILSON, J. T., Some major studies of the Canadian Shield, Can. Min. Metal. Bull., Trans., v. 52, pp. 231-242, 1949.

University of Western Ontario,
London, Ontario, Canada

(Communicated manuscript received May 21, 1951;
open for formal discussion until March 1, 1952.)

Transactions, American Geophysical Union Volume 32, Number 5 October 1951

THE PROBLEM OF SAFE YIELD IN INSULAR GHYBEN-HERZBERG SYSTEMS

Chester K. Wentworth

Abstract--Where the lower boundary of fresh water in a Ghyben-Herzberg lens is of area comparable to the area of the aquifer, changes in vertical position yield large amounts of water which may be equivalent to several months or years of annual increment from rainfall. Draft on such a system may not immediately develop indication of water shortage but may trend over a long period toward conditions unfavorable to maintenance of a desired quantity or quality of water. Changes in the amount of ground-water storage are often not practically measurable, even when a reasonable total inventory suggests that storage is being depleted. To determine in such a system what yield is safe is as much a social problem as a hydrologic one, and involves contemporary and future patterns of normal and emergency use, viewed in the light of long-term conservation aims. Physical and hydraulic data are essential but ultimate evaluation must take account of the probable future state of the community and existence or non-existence of alternative future supplies.

Introduction--The phrase "safe yield" at once connotes a concern for the continuance of a good, potable supply or of the hydrologic system from which the water comes. Yet the great variety of systems furnishing water will tend to limit the application of any specific definition of such a phrase unless it be of rather cumbersome and generalized wording. Because the discussion of such matters often centers around experiences in the eastern, or the western, part of the United States, where little or no volumetric relationship to ocean water is involved, it seems desirable that the Pacific Islands be heard from.

The determination of safe yield for the total and the several components of the water-supply system for Honolulu on Oahu has been for many years recognized as most important, but the advance in philosophic understanding greatly exceeds present capacity to make satisfactory or reliable estimates. This condition rests in part on the large ratio between storage and daily quantities used. On the other hand, during the war in the Pacific there was an enormous range of experience with small and medium-sized island ground-water lenses in balance with sea water, many of which were utilized beyond either their safe capacity or at least the safe draft permitted by the depth and other characteristics of the well. Many of these were quickly exploited beyond their suitable capacity according to peacetime standards, as was generally recognized, but at the same time the data on rainfall, static heads, rates, and times of pumping were not adequately collected or preserved and most of our understanding is therefore only qualitative. A great many laymen, both of the armed services and among the natives, are well aware of the danger of exceeding some limit in any given place, but neither they nor the water-supply engineer or geologist have as yet an adequate basis for formulating such a limit.

Factors in definition--The chief difficulty inheres in the concept of safety, which in turn rests on standards of use, capacity for disciplined behavior, and other characteristics of the users, as well as the actuarial vagaries of the atmospheric and ground conditions. A rate of yield and use at any given time is safe if it does not threaten, under contemporary or foreseeable future conditions, to be greater than the available supply through the immediately applicable methods of pumping and delivery, and subject to limits of potability, salinity, and the like deemed suitable at that time and place.

Many of the difficulties in estimating safe yield stem from the lag between augmented or excessive draft and the slow depletion of large or remote related water bodies or other slow processes similarly set in motion. In Honolulu it is believed that following the lowering of basal water heads during dry periods or by heavy draft, the related shrinkage of the bottom part of a thick Ghyben-Herzberg lens may not be completed for many years or possibly several decades. Under such a condition it is evident not only that there is yielded to the wells, causing the water table lowering, a large amount of water that does not come from recent rainfall, but also that the amount of water taken is not related in a simple fashion to the rate and area of feeding rainfall, and the corresponding yield cannot be accurately estimated.

Storage effects--This storage feature of the Ghyben-Herzberg lens, whereby the total accumulated water may be of the order of 40 times the amount above sea level, is of great importance, since the changes in bottom storage set in motion by a given change in the water table above sea level are likewise of a potential volume which may approximate 40 times that of the immediate change in top storage. This is shown to a remarkable extent at Honolulu, where the caprock formed by the coastal structure restrains the escape of fresh water, produces an artesian condition with heads that were originally 30 to 40 ft, and with the fresh water extending more than 1000 ft below sea level. In the event of draft exceeding the rate of immediate inflow to the water table, with consequent lowering of the water table, there is induced a flow from the bottom storage which, with any rates attainable by existing pumps, may soon damp off further lowering of the water table. This means that in any functional Ghyben-Herzberg system contained in a three-dimensional aquifer having a salt-water - fresh-water boundary comparable in area to the water table and just beneath it, with excess draft at a rate over the contemporary infiltration increment, there is set in operation a boosting effect which tends to greatly augment the amount of water available.

While this effect is of great practical value in meeting fluctuations of demand and makes possible rates of draft in excess of long-term increment for periods of months or years according to the size of the system, it defeats any simple or short-term approach to estimating safe yields.

It is evident that an unsafe yield is one which under any given set of conditions leads to shortage of water, inadequate reserve, impairment of quality, or other adverse effects on the user or adjacent claimants who may have rights to water or continuance of certain conditions. In Honolulu, there is small risk at present of abrupt shortage of water. However, it is known that continued draft at rates now obtaining has progressively lowered the basal heads and that in response to this change, the zone of transition between salt and fresh water is rising and some of the deeper wells have been suffering salt encroachment for many years. This change has not yet reached the wells chiefly used for city supply, but there is little doubt that it eventually will do so and plans have been drawn for substituting tunnels at, or slightly above, sea level for the existing wells. Such so-called skimming tunnels will be far less susceptible to salt encroachment.

Effect of head reduction--The point has been made, and properly, that lowering of the level of operation of the system will reduce leakage toward the ocean and hence increase somewhat the amount of water available from contemporary rainfall. Whether such a change should gradually be made depends on the relative value of a large reserve storage including ultimately all the water contained in the portion below sea level and the increased yield made available by the changed conditions of draft. Whatever may be the ultimate level of operation, it appears at least that rapid or drastic changes are not feasible and that such possibilities do not modify what might be called the immediate safe yield. On the other hand, there is in process a slow retirement of artesian wells because of need for recasing and a substitution of draft from so-called skimming tunnels. This in time will lead to a practical feasibility of operation at somewhat lower levels. In course of the lowering of head and the thinning of the bottom portion of the Ghyben-Herzberg lens there will be a reduction of the amount of water coming from this change in volume of storage. Over a considerable period the increased water coming from storage will be added to water gained by reduction of leakage through the caprock to the sea and there will thus be the appearance of a greater gain than can be expected to be permanent. Since the gain from reduction of storage in a large system may amount to several million gallons daily and a considerable fraction of the daily usage, and may continue over a period of one or two decades, it is essentially impossible to estimate the true value of the residual gain due to the reduction of head.

Other long-term factors--Under such conditions any estimate of the amount of safe yield, and particularly the meaning of the term "safe" must involve not only the present pattern of development and usage of water but also the possible future changes in methods and conditions of draft as well as the future amount and conditions of demand. Present practices might be pursued for a decade or more without creating serious contemporary water stringency but, on the other hand, may trend toward depletion of storage and the slow creation of conditions that would be quite untenable for future generations. In support of practices that appear to be unsafe in a long-term sense, it is often asserted that newer and more highly mechanized methods ("Science will find a way!") will make possible a more effective utilization or will obviate need for storage now thought essential.

There is here posed a question as to how far the people and the public authority of one generation are ethically justified in so operating that a future generation is deprived of freedom of choice as to methods of operation. A more defensible doctrine would hold that one generation should not wittingly so over-exploit or otherwise impair the conditions of yield of a renewable natural resource as to prevent a future generation from exercising a reasonable choice as to methods and levels of

development, or from retreating, if it so desires, to a more conservative pattern.

The foregoing discussion leads us to the following outline of factors affecting a safe or justifiable yield or draft.

(1) Daily, monthly, or annual quantity of water moving through the hydrologic supply system.

(2) Probability pattern of fluctuations above or below the mean amounts for various periods.

(3) Amount of storage in relation to daily, monthly, or annual averages in bodies readily accessible to draft.

(4) Possible effect of changes in ordinary storage on average amounts available. (Here enters the extremely potent 40:1 effect of the Ghyben-Herzberg principle.)

(5) Effects of changes of storage on rates of flow or on existence of flow or possibility of draft with existing machinery and installations.

(6) Indicated future trends and reliability of estimates as to quantities and conditions of usage.

(7) Effects of methods of exploitation, rates of draft, and of levels of maintained storage on quality of water. (Both salinity and sanitary quality are involved.)

(8) Relationship of area in question to adjacent areas with which helpful coordination might be achieved.

Application of these factors to a large system comparable to that of Honolulu--(1) Direct and categorical determination of periodic amounts can be accomplished only with low precision because of effects connected with (2), (3), (4), and (5), above.

(2) Probability patterns are determinable with fair precision as the periods of record increase to several decades.

(3) Direct determination is quite difficult but statistical analysis of residual deviations may yield data on orders of magnitude.

(4) Effects are probably large but satisfactory determination is difficult in any short period or without laborious analysis.

(5) Not too difficult of resolution with unified control but very little immediate solution with diverse ownership.

(6) Depends on social and economic prospect of community.

(7) Determinable only very slowly and chiefly as result of inadvertent empiricism.

(8) To some extent in some island areas augmented water supply can come from less developed adjacent areas, particularly if the soil and topography of the adjacent area be less favorable to agriculture or settlement. But in many islands the total water supply is sharply limited by the area of the island, and the possibility of bringing water from distant areas is nil.

Application of these factors to a small, isolated oceanic island--(1) Many such islands lack rainfall measurements over sufficient period to yield valid averages and reliable probability patterns of variability. Beyond very rough placement in climatic belts little information is commonly available and rainfall totals for various periods in some of these belts are extremely variable. Measurements of water-table elevation or flow in established streams, if any, are rarely available.

(2) Local determination has rarely been accomplished but a competent hydrologist may be able to make useful, outside estimates of variability, taking account of the climatic belt and known patterns so far as data are available.

(3) Only extremely rough estimates can be made, but some evaluation should be attempted.

(4) and (5) These factors, in conjunction with (7), are of paramount importance and, for their evaluation, continuing and systematic measurements of water quantities, qualities, and water-table elevations should be made.

(6) In such small islands the issue of water supply is either one of immediate concern or is based on a specific proposed utilization where laissez faire trends are not involved.

(7) See (4) above.

(8) If the island is truly isolated, this factor is negative.

Summary--From the various considerations set forth above it appears that in a large Ghyben-Herzberg system where the total storage in the lens above and below sea level is of the order of 20 times the annual rainfall on the same area and perhaps 50 to 100 times the annual ground-water circulation, the direct contemporary measurement of safe yield or increment yield is impossible. On the other hand, when the consideration of various lags and cycles takes in a period of several decades, there is likely also to be involved a number of social and technical trends of equal duration which are also not susceptible of categorical evaluation. The problem thus becomes one of progressive approximations in the light of such hydraulic and social facts as can be ascertained and the quantity of water is better spoken of as justifiable draft rather than safe yield.

With respect to a small, isolated island, where the lens of fresh and brackish water may be only a few feet in thickness, the term "safe" is more suitable, since the storage of usable fresh water in the Ghyben-Herzberg lens may here be no more than a few weeks or months of groundwater circulation. In fact, it is often the case that owing to the precarious condition of freshwater circulation at sea level, the Ghyben-Herzberg lens may furnish no water of low salinity or may be subject to immediate and rather rapid increase in salinity when a draft of useful rate is applied. Here the determination of how much water can be drawn under given salinity limits and how the amount may be moderately increased by suitable design of a well or tunnel becomes at once a practical problem. The greatest caution and conservatism must be employed in interpreting results of measurement of water levels, quantities, and qualities, since the principle still holds that any draft from such a balanced natural water body must at first consist both of yield from some combination of recent rainfall and of water derived from reduction of storage. Only a long period of steady draft under new conditions will indicate what steady quantities and qualities can be expected and it can be extremely costly if early increases of quantity without adequate analyses of quality are accepted too optimistically.

Hawaiian Volcano Observatory,
Hawaii National Park, Hawaii

(Manuscript received March 10, 1950; open for formal discussion until March 1, 1952.)

Transactions, American Geophysical Union Volume 32, Number 5 October 1951

A CRITIQUE OF GEOTECTONIC ELEMENTS

Paul D. Krynine

Abstract--The current classification of geotectonic elements--geosynclines and cratons--as proposed by Bubnoff-Stille-Kay and summarized by CADY [1950] is morphologically comprehensive, but not adequate genetically in terms of structure, process, and stage. Cady does not mention the contributions to the understanding of geotectonic elements made by sedimentary petrologists. A purely spatial approach (analogous to Bubnoff's structural approach) relates sediments either to regions of relative stability or to regions of great subsidence. This approach was originated by BAILEY [1936], JONES [1938], and particularly TERCIER [1939], followed by PETTIJOHN [1943, 1949], and Krumbein-Sloss-Dapples. Their criteria cover gross lithology, bedding, sorting, and limited aspects of mineral composition. Since rate of subsidence alone is taken as a basic factor, all of these schemes are naturally incomplete and furthermore contain no definite chronologic tie-up between sedimentary and geotectonic stages.

A spatial-chronologic scheme (analogous to Stille-Kay) was preliminarily expounded by BERTRAND [1897] and completely worked out by the author in 1941. The author relates tectonic movements of both the subsidence and uplift type to mineral composition (above all), to texture, structure, and field distribution, and hence classifies sediments and geotectonic elements into three basic interdependent classes related in space and time and characterized by first- and second-cycle orthoquartzites, low- and high-rank graywackes, and arkoses.

Some problems of the mutual relationships between the geotectonic elements that built the continental and near continental portions of our planet have been brought sharply into focus in this journal by the recent paper of CADY [1950]. One of these problems is that of genetic classification. Geotectonic elements, such as geosynclines of various breeds and hues, have been profusely described, particularly in respect to their external geometry and morphology. Furthermore, in some of the papers quoted by Cady and in the article by Cady himself, the morphological description of these structural or geotectonic elements is related to stages of development of continental border regions, but this is not a genetic classification. The genetic description (and classification) of any entity implies a recognition of the original state or condition, a definition of the processes which changed this original condition and a formulation of how far such modification has proceeded.

Geotectonic elements, such as geosynclines and cratons, can be considered as super landforms, that is, depressions or protuberances in the crust of the Earth, like the "furrows" and "welts" of Bucher. These major landforms do not develop in a vacuum; they are superimposed upon some pre-existing conditions in the Earth's crust, they are formed by certain processes, and they reach a certain stage of development. Hence, it seems that the classical principle of the description and classification of landforms as introduced by W. M. Davis--the concepts of describing landforms in terms of structure, process, and stage--could be fruitfully applied to the classification of geotectonic elements. This powerful generalization of the immortal Davis is indeed the great "universal solvent" of geology, and no subject in the Earth sciences contains problems that would not yield to this method, providing that adequate data can be gathered.

The structure of the Earth's crust is the pre-existing set of conditions that prevailed at the time when any given period of tectonism was initiated. This is a fertile field for future studies, since we do not seem to have, at the present time, even the faintest idea of what is meant by this. Process is, again, something that apparently no worker in the field of geotectonism has been able, up to the present, to express with much clarity, or at least with pragmatic usefulness. The large number of structural publications dealing with the supposed details of the final operative mechanisms of local crustal deformation or conversely covering the more hypothetical aspects of the broad final causes of crustal deformation in general have not suggested as yet any simple and effective way of gaging (that is, comparing effectively) the actions of the processes responsible for the formation of geotectonic elements, such as geosynclines. Finally, stage can be reasonably well inferred from our present knowledge, but by itself this is not of much value.

If a workable way should be gained of expressing structure and process, then the problem of the genetic classification of geotectonic elements will be well on its way toward solution. Perhaps

workers in this field have been too concerned with effects and have not given sufficient thought to the causes in terms of dynamic processes. Perhaps an entirely new approach is needed; perhaps we have been overemphasizing the minutiae of comparative morphology (the vergleichende Beschreibung approach of the German scientists) without having a clear idea of what common, or rather fundamentally basic common, factors we would be trying to compare. Indeed, much of the involved terminology employed at the present time has become so complicated and so controversial as to lose much of its value, without particularly advancing the problem. This has happened frequently in geology. For instance, the classification of ore deposits introduced by the great von Cotta in 1859 is morphologically descriptive and comprehensive, but it did not lead to an understanding of the proper relationships among metallic ores. It remained for Lindgren to change entirely the viewpoint of mining geology with his genetic approach. What is necessary now is not so much a new super-comprehensive classification and super-detailed description of every possible morphological feature of structural basins and stable (?) areas, but rather a few simple unifying concepts based on the forces and conditions that produce these geotectonic elements. The descriptive and interpretative achievements of von Bubnoff, Kay, and particularly Stille deserve great praise; with this excellent background, future work may easily be directed toward the more dynamic aspects of the problem.

Cady's excellent presentation of the status of our present knowledge of geotectonic elements in space and time contains a comprehensive review and brief evaluation of the ideas held by different workers in this field. This, in itself, makes it the more regrettable that Cady has not given the same type of treatment to the second part of his paper, which deals with the magmatic and particularly the sedimentational associations which characterize the various geotectonic elements. After all, a geosyncline or craton does not exist in the abstract and cannot be described as such from the mere fact of its inferred--or alleged (?)--presence. Geosynclines are not different from landforms, which are made up of certain rocks, frequently aggradational, and cannot be divorced from these rocks: a dune does not exist without its sand. Similarly, a geosyncline can be recognized only because it is a certain body of sedimentary rocks, consisting of certain rock types put together in a certain way. The shape or even existence of an ancient geotectonic basin cannot be determined if its sediments are not there and have not been described. Hence, a brief review of the evolution of current ideas and progress made in this field seems in order. Since Cady's otherwise commendable paper does neither discuss nor present in his list of references one single publication dealing with an attack upon the origin of geosynclines and other geotectonic elements by sedimentary petrographers, who, after all, have produced considerable evidence toward the establishment of the concepts stated by Cady, it may be worthwhile to repair this omission by giving here a brief discussion of this subject.

The credit for recognizing the types of sediments that characterize the different stages of the development of a geosyncline, and furthermore presenting the description in an aspect which, regardless of its stark simplicity, is more modern than most of the publications that have seen the light during the past few years, belongs to the classical work of MARCEL BERTRAND [1897] which deserves the greatest recognition. Bertrand's typical geosynclinal sequence is: (1) Subsidence of the old rock basement, which, when it reaches great depths, may be considerably metamorphosed, and even intruded by granite, thus forming the basal gneissic facies. (2) Formation of one single large geosyncline, which gets rapidly filled with debris, usually fine-grained; after deep burial it may be metamorphosed, but less so than the basement. This forms the fine-grained or shaly Flysch facies, or, if metamorphosed, the slaty and phyllitic (schistes lustrés) facies. (3) Uplift of the central part of the geosyncline and formation of two border geosynclines which get rapidly filled with coarser eroded debris from the reworked older sediments, thus forming the coarse (true) Flysch facies (Flysch grossier). (4) Final folding and uplift of these geosynclines, and deposition, at the foot of these mountains by the erosion of older sediments, of very coarse grits, conglomerates, and sands, frequently red colored. This is the coarse molasse (or grès grossiers et rouges) facies.

Following Suess' concept of four great orogenic cycles, Bertrand claims this same typical succession, at least partially, for the great mountain chains everywhere on the globe: Huronian, Caledonian, Hercynian, Alpine. This certainly sounds familiar, and appears very much like Stille's concepts. Bertrand's conclusions are well documented for the Alps and the European coal measures, but are somewhat hypothetical for his American examples.

Clearly Bertrand's geosynclinal space-time facies are not so different from Cady's tabulation, and although mistakes can be found in every point of Bertrand's scheme (particularly his metamorphism) its overall approach to the truth is extraordinary.

Bertrand failed to connect the occurrence of the well-sorted orthoquartzites and dolomites of the earliest stable regions (such as the continental (?) block and its weakly mobile shelves) with

the lateral approaches of a geosyncline. This failure may be because of the fact that these relatively stable facies, as a whole, are very rare in Western Europe; outside of the Russian platform, Europe is a highly deformed, contorted peninsula and lacks the great stable cratonic (?) platform or shield areas of the North American, Asiatic, and African continents. This "sampling error," so common in geology, prevented Bertrand from giving the full picture of a complete geosynclinal cycle. Hence, Bertrand's scheme lacks the first cycle orthoquartzites that should be sandwiched between his facies 1 and 2. As is usual with great pioneering work done before its time, Bertrand's ideas were promptly forgotten.

More than 40 years later, BAILEY [1930, 1936] and JONES [1938] brought out the concept that there is a considerable difference between the relatively well-sorted, clean-looking, and cross-bedded sediments formed on allegedly stable platforms or shelves and the poorly sorted, dirty looking, and graded bedded sediments of the graywacke type formed in rapidly subsiding geosynclinal regions. The sedimentary differences between geosynclinal and epicontinental regions had been studied before in terms of gross stratigraphic differences by innumerable workers, beginning with Dana, Gilbert, and Suess, but Bailey and Jones expressed these differences in reasonably usable lithological terms. The textural ideas of Bailey and Jones are sound, but the graded versus cross bedded criterion is loaded with such a formidable array of exceptions and qualifications that it has led to serious mistakes by later students. This work brought to the fore the idea that the type of sedimentation is controlled by the rate of subsidence, a development of BARRELL's [1917] idea that the amount of sedimentation is also controlled by the rate of subsidence. This emphasis on rate of subsidence (regardless of any lip service to uplift) has remained the cornerstone of all subsequent efforts, except those of Krynine.

PETTIJOHN [1943], in his study of Archean sedimentation, presented much better petrographic evidence that either Bailey or Jones on the differences between the platform type of well-sorted sandstones, associated with carbonates, and the graywackes of the geosyncline. However, he followed Bailey and Jones in expressing these differences in terms of texture and bedding.

TERCIER [1939], on the basis of his work in the Dutch East Indies, expanded the rate of subsidence concept considerably by marrying sedimentary environments, bathymetric regions, and structural (or geotectonic) elements to form five classes of environments of sedimentary deposition: (1) continental sedimentation; (2) paralic sedimentation on continental platforms; (3) shallow marine sedimentation on the same platforms; (4) geosynclinal sedimentation; and (5) abyssal sedimentation. A very detailed textural description of related sediments was appended. Tercier, however, did not discuss the possible sequence in time of the elements which he had distributed in space. Later, TERCIER [1946] reformulated his ideas with the help of graphic tables.

Tercier set the pattern for much of the later work in the United States. For instance, PETTIJOHN [1949] produced a detailed classification of "functional" or tectonic environments. This classification, after dividing sediments into tectonic and non-tectonic classes, takes the tectonic sediments and splits them again (following Bailey and Jones) into orogenic or geosynclinal types and epeirogenic or platform types. These types are a combination of Tercier's regions of deposition, Bertrand's and Krynine's post-orogenic facies, and quite a few of Twenhofel's geographic environments. The scheme is indeed comprehensive; its practical value for geotectonic interpretation will have to await the test of time; its possible weakness is overemphasis of the rate of subsidence.

Pettijohn's petrographic descriptions, mostly (but not always) follow Krynine's terminology and many of his rock types can be fitted as single units into a good part of the geotectonic elements tabulated by Cady. As a whole, Pettijohn does quite well in matching thickness, lithology, and texture against possible stable versus unstable regions. Both Pettijohn and the Northwestern school study space rather than time relationships, this being analogous to the von Bubnoff approach to geotectonism. They quote, but do not utilize, the author's ideas of the diastrophic and geosynclinal cycle of sedimentation.

The Northwestern school of Krumbein, Sloss, and Dapples has elaborated these space relationships, although not always in a particularly clear way, in a voluminous series of papers published from 1947 onward. The latest [KRUMBEIN and SLOSS, 1951] Northwestern scheme of structural (or geotectonic) forms and related sediments is as follows: (1) stable shelf; (2) unstable shelf; (3) intracratonic basin; and (4) geosyncline. There is a large repetition of diagnostic criteria and a corresponding duplication of the none too rigorously defined petrologic types that are said to be related to each of these four tectonic classes. This applies particularly to the so-called subgraywacke and its disguised, but easily unmasked, relatives such as the salt and pepper sandstones and the quartz-muscovite sandstones, which are spread throughout the whole range of

the Northwestern tectonic and depositional units. The Krumbein-Sloss-Dapples scheme is a frank attempt to make sediments fit into a somewhat simplified version of the detailed geotectonic classification of Stille and Kay. The very moderate success of this effort suggests that the proper genetic bridge between sedimentation and tectonism has not been quite established. This may be due to the Northwestern approach, and possibly also to some inherent properties of the geotectonic classification itself.

Working along different lines, KRYNINE [1940] proceeded considerably beyond the concept of the control of sedimentation by the rate of subsidence and hence beyond the conventional spatial division into stable platforms (or shelves ?) and the subsiding geosynclines reinforced by the numerous, but subordinate, subdivisions of the preceding workers.

KRYNINE's [1941abcd] idea is that tectonism controls not only the rate of subsidence and the shape of geotectonic elements and related basins of deposition,[a] but also controls to an equal degree the character of the source area, both in respect to relief (an obvious derivative of tectonism) and, what is equally important in respect to petrography, mineral composition. This last idea is based upon the fact that different layers of the Earth's crust (of different composition) are preferentially eroded during different stages of uplift and, conversely, of related subsidence in the basin of deposition. Furthermore, prior to uplift, these future source areas, if consisting of early geosynclinal sediments, may be metamorphosed, or magmatically injected, again according to the same pattern of tectonic control. In a nutshell, the relations between diastrophism and sedimentation consist of numerous interdependent factors, which must be considered as a whole and cannot be split into independent variables. Emphasis on one single variable, such as rate of subsidence in the basin of deposition, may lead to highly misleading results.

These concepts were evolved as a result of very detailed petrographic work done principally on a comprehensive assortment of Appalachian sediments (1931-1940) reinforced by similarly detailed studies on less extensive, but sufficiently representative, rock studies from other parts of the globe, varying from Great Britain to Burma. By detailed petrographic work is meant a study of sedimentary rocks on the basis of thin sections, carried at least with the same degree of professional competence as expected in igneous and metamorphic petrography of the research type.

Krynine's diastrophic or tectonic cycle combines subsidence with uplift, both in space and in time, and thus makes it possible (1) to classify sediments genetically in terms of areas of different tectonic activity (space relationships), which follow each other in a certain order (time relationships); and (2) to equate these areas with the morphologic units of the geotectonic cycle, such as geosynclines.

Incidentally, this work proved to be successful only because a petrographically valid system of classification of sediments had at the same time been evolved by KRYNINE [1942, 1948 based on texture and mineral composition] which had made it possible to recognize and differentiate significant differences between sedimentary types.

KRYNINE's [1940, 1941abcd, 1943, and particularly 1942] early versions establish the following diastrophic stages, which (as stated before) use an interchangeably synonymous terminology of tectonic, morphologically-structural, and geomorphic derivation.

(1) Pre-geosynclinal or quiescence or epicontinental or peneplanation stage--Operative at the beginning of rhythmic subsidence on and outside the edges of the continental stable platform following peneplanation and characterized petrographically by first-cycle orthoquartzites and carbonate rocks. This stage is equivalent to portions of the stable parts of the continental block and to the beginning of the mobile shelves of the stage 1 of primary geosynclinal formation as characterized by Cady. This stage was mistakenly labeled as early geosynclinal by Krynine in one of his 1941 abstracts.

(2) Moderate deformational or geosynclinal stage proper--This was divided by Krynine into several sub-stages with modifications by warping, faulting, and metamorphism.

---

[a] These two, that is, geotectonic elements and depositional basins, are entirely different things, although this fact has been misunderstood without exception by every worker in this field (including the writer) and the terms used interchangeably by everybody, a great and confusing mistake. Beginning with 1943, the writer has attempted to differentiate between these two items.

(a) Early geosynclinal, characterized by the formation of a geosyncline with a less violently subsiding flank near the continent (equivalent to the mobile shelf of Cady's stage 1) and strongly subsiding outward flank, which gets rapidly filled with high-rank crystalline and volcanic detritus of the high-rank graywacke type. This is equivalent to the eugesynclinal zone of the same primary stage.

(b) Main geosynclinal, beginning with great subsidence and burial of the outward flank, followed by minor mountain-making revolutions of the Taconic type, with metamorphism and formation of phyllites and slates. This is followed by warping, uplift, and erosion of this metamorphosed material of the eugeosyncline into the more slowly subsiding geosynclinal trough near the continent, which may be labeled either as miogeosyncline or foredeep according to the Stille-Kay pattern. The associated rocks are low-rank graywackes, consisting of low-rank metamorphic rock fragments (slates and phyllites) and second-cycle reworked orthoquartzites. At this stage, the geosyncline is autocannibalistic; it feeds upon its own flank. This clearly corresponds to stage 2, or primary mountain-building stage of the geotectonists. Up to 1943, the author did not realize that the inner and outward portion of a geosyncline, that is, the "miogeosyncline" and "eugeosyncline" zones, may possibly be separated by some sort of a stable nucleus. Hence, he conceived this substage of the deformation as differential deformation of one large trough. This was because of failure to distinguish properly between the low-rank or common or non-feldspathic graywackes (characteristic of moderate deformation such as mobile shelves and miogeosynclines) and the relatively rare high-rank or plagioclase-bearing graywackes, which are associated with rapidly subsiding deep troughs of the eugeosynclinal type. Low-rank graywackes consist of low-rank metamorphic rock fragments and very little feldspar (up to ten per cent); high-rank graywackes, in addition, contain much plagioclase and chlorite, whereas arkoses carry K-feldspar and kaolin. Never confuse these two; granites are also different from gabbros. This concept was modified in 1945 and 1946 with a corresponding distinction between eugeosynclines and miogeosynclines as separate entities with separate types of sediments. This is illustrated in the section of the Appalachian region in the Guide Book of KRYNINE [1946, p. 16].

(c) A later stage of increasing deformation of the entire geosyncline, with warping and uplifts of the flanks characterized by the accumulation of large amounts of low-rank graywackes, which Krynine in his earlier ideas equates tectonically with the Alpine molasse. This stage culminates in compressive faulting and magmatic intrusion. Krynine conceives of the stage as consisting of rapid mountain-building episodes of variable intensity, punctuated by periods of slow deformation, before the final closure of the geosyncline. This corresponds to stage 3, the stage of secondary mountain building of Stille-Kay-Cady.

(3) The stage of violent deformation, or post-geosynclinal or orogenic stage or stage of violent vertical tectonic uplift--This follows magmatic intrusion and is characterized by block faulting and the formation of very coarse material, frequently arkosic if the granites should be block faulted at that time. These sediments are generally continental, found on piedmonts. This stage precedes final peneplanation of the new craton and corresponds to stage 4, or the final differential uplift and local subsidence concept of the geotectonists.

Hence, a geotectonic classification scheme was produced, which in essence is not so very different from Cady's synthesis of 1950, although admittedly the author's classification neither carries nor pretends to carry much of the geotectonic and morphologic detail of Stille and Kay. This early (1940-44) scheme of the author is now probably somewhat out-of-date, and contains numerous errors, but is still reasonably usable. Its revision is on the way.

Insofar as purely sedimentational associations are concerned, CADY's [1950] scheme follows substantially Krynine's earlier presentation, including the terminology introduced by KRYNINE [1941abcd], which since then has become standard, such as first- and second-cycle orthoquartzites. However, Cady, in a very praiseworthy way, contributes many examples in illustrating these associations, thus extending our knowledge in this direction.

Summarizing, this review, with its chronologic recitation of dates, has three aims.

The first is to show that there has always been a parallelism between structural and sedimentary concepts of tectonism from the days of Dana (geosyncline) and Gilbert (epi-orogenesis). Investigation of purely structural spatial relationships of geotectonic elements reached its climax in the work of von Bubnoff and the equivalent sedimentational aspect in that of Tercier, Jones, and their followers. Purely structural time relationship studies of geotectonic elements, superimposed and following upon spatial relationships, resulted in the classification systems of Stille and Kay. In the combined realm of sediments and tectonism, however, time relationships were immediately united with spatial relationships, in a preliminary form by Bertrand (as early as 1894) and in a reasonably complete way by Krynine. Bertrand's geotectonic ideas are highly prophetic of Stille's later concepts.

The second aim is to emphasize that a successful solution of the problem of describing and classifying geotectonic elements was achieved by methods of classic petrography (as applied to sediments) as early as 1940-42. This is exactly the same time period (1940-42) when the problem was being treated, also quite successfully, by the conventional methods of structural geology and stratigraphy. It is desired to bring to the attention of the geologic profession, and to bring this with considerable emphasis, that these successful geotectonic results were indeed obtained by petrography, and furthermore these results were obtained rapidly in a short period of time and with less effort than would have been the case with conventional geologic methods.

The third aim is to point out the desirability of a more genetic approach in future studies of geotectonic elements, whether carried out by conventional geologic or by petrologic methods. Such an approach should be in terms of W. M. Davis' principle of structure, that is, pre-existing condition, process and stage.

References

(Limited to the sedimentological aspects of the problem of geotectonic classification)

BAILEY, E. B., New light on sedimentation and tectonics, Geol. Mag., v. 67, pp. 77-92, 1930.

BAILEY, E. B., Sedimentation in relation to tectonics, Bull. Geol. Soc. Amer., v. 47, pp. 1713-1726, 1936.

BARRELL, J., Rhythms and the measurement of geologic time, Bull. Geol. Soc. Amer., v. 28, pp. 745-904, 1917.

BERTRAND, MARCEL, Structure des Alpes françaises et récurrence de certain faciés sedimentaires, C.-R. Cong. Geol. Intern., 16th Session, 1894, pp. 161-177, 1897.

CADY, WALLACE M., Classification of geotectonic elements, Trans. Amer. Geophys. Union, v. 31, pp. 780-785, 1950.

JONES, O. T., On the evolution of a geosyncline, Proc. Geol. Soc. London, v. 94, pp. 60-110, 1938.

KRUMBEIN, W. C., and L. L. SLOSS, Stratigraphy and sedimentation, Freeman and Co., San Francisco, pp. 497 + viii, 1951.

KRYNINE, PAUL D., Petrology of the Third Bradford Sand, Pennsylvania State College Mineral Ind. Bull. 29, State College, Pa., p. 134, 1940.

KRYNINE, PAUL D., Differentiation of sediments during the life history of a landmass, Bull. Geol. Soc. Amer., v. 52, p. 1915, 1941a.

KRYNINE, PAUL D., Paleogeographic and tectonic significance of sedimentary quartzites, Bull. Geol. Soc. Amer., v. 52, pp. 1915-1916, 1941b.

KRYNINE, PAUL D., Paleogeographic and tectonic significance of graywackes, Bull. Geol. Soc. Amer., v. 52, p. 1916, 1941c.

KRYNINE, PAUL D., Paleogeographic and tectonic significance of arkoses, Bull. Geol. Soc. Amer., v. 52, pp. 1918-1919, 1941d.

KRYNINE, PAUL D., Differential sedimentation and its product during one complete geosynclinal cycle, Proc. First Pan-Amer. Cong. Mining and Geology, Santiago, v. 2, pp. 537-561, 1942.

KRYNINE, PAUL D., Diastrophism and the evolution of sedimentary rocks, Syllabus, Distinguished Lecture Comm. Amer. Assn. Pet. Geol., Tulsa, 20 pp., 1943.

KRYNINE, PAUL D., From the Cambrian to the Silurian near State College and Tyrone, Pa., Guide Book, 12th Annual Field Conf. of Penna. Geol. (first part), 32 pp. (mimeographed), 1946.

KRYNINE, PAUL D., The megascopic study and field classification of sedimentary rocks, J. Geol., v. 56, pp. 130-165, 1948.

PETTIJOHN, F. J., Archean sedimentation, Bull. Geol. Soc. Amer., v. 54, pp. 925-972, 1943.

PETTIJOHN, F. J., Sedimentary rocks, Harper Bros., New York, 526 pp. + xv, 1949.

TERCIER, J., Dépots marins récents et séries géologiques, Eclogae Geol. Helvetiae, v. 32, pp. 47-100, 1939.

TERCIER, J., Problèmes de sédimentation dans l'Insulinde, VSP Bull. Verein. Schweiz. Petroleumgeologen und Petroleumingenieure, no. 44, pp. 7-19, Nov. 1946.

School of Mineral Industries,
The Pennsylvania State College,
State College, Pennsylvania

(Communicated manuscript received February 27, 1951;
open for formal discussion until March 1, 1952.)

PROGRESS REPORT, SEISMOLOGICAL LABORATORY, CALIFORNIA INSTITUTE OF TECHNOLOGY, 1950

H. Benioff, B. Gutenberg, and C. F. Richter

(Contribution No. 514, Division of the Geological Sciences, California Institute of Technology, Pasadena, California)

In addition to the papers published during 1950 (list at end), the following research activities have been carried forward.

Instrument development under Benioff has involved further modification of the capacity-transducer seismometer mentioned in our previous report. In its present form the mechanical moving member is positioned between two fixed capacitor plates so that motion of the member produces capacity increments of opposite sign in the two condensers formed between the fixed and moving members. The two condensers are shunted by inductances of equal size so mounted as to have low mutual coupling. The two tuned circuits thus formed have the same resonant frequency--approximately 10.75 mc. The two inductors are coupled to the output circuit of an electron-coupled frequency doubling crystal oscillator operating at 5.35 mc fundamental frequency. When the moving mechanical element is positioned midway between the two fixed capacitor

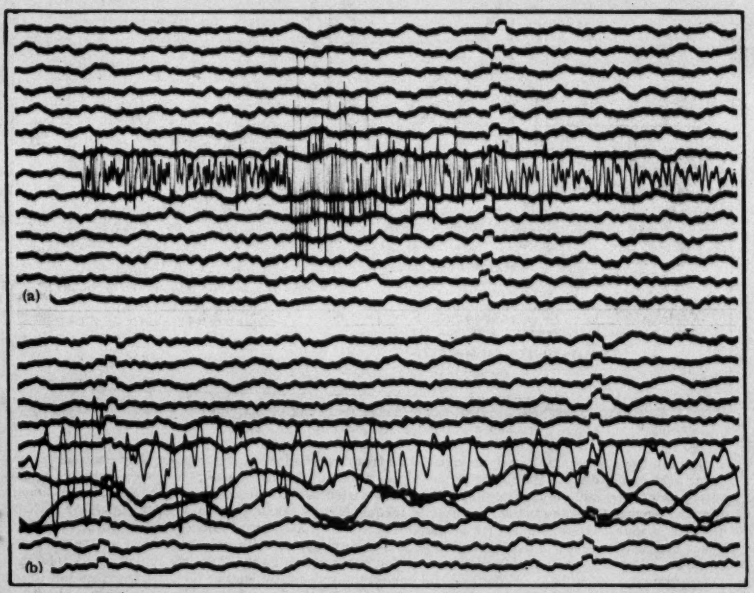


Fig. 1--Seismogram written with capacity-transducer seismometer (T_0 = 1.5 sec) and 0.1-sec galvanometer: (a) small local earthquake; (b) teleseism, January 6, 1950 near ϕ = 27.5°N, λ = 81°W, h = 100 km, M = 7.0

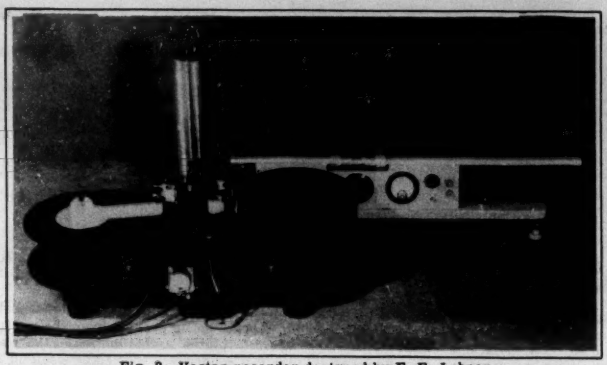


Fig. 2--Vector recorder designed by F. E. Lehner

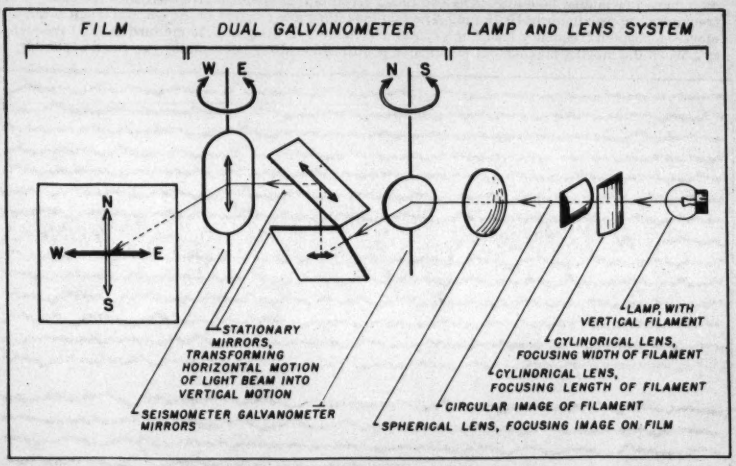


Fig. 3--Schematic drawing of dual galvanometer and optical system of vector recorder designed by F. E. Lehner

plates the two circuits are each detuned 50 kc from resonance, at which point they each have currents approximately 0.7 times the values at resonance. The two tuned circuits operate two oppositely poled germanium crystal diodes whose rectified outputs are connected to a resistive bridge circuit. Output from the bridge at seismic frequencies is taken through a large capacitor which with the bridge resistors has a time constant of 100 or 1000 seconds depending upon the application. The instrument has demonstrated good stability for use with galvanometers having periods from 0.1 to 15 seconds. With 90-second-period galvanometers the stability is not yet satisfactory. Operating on a pendulum with one-second period the transducer output is approximately ten times the maximum required to drive a 0.1-second galvanometer for satisfactory recording of short-period microseisms at Pasadena. Figure 1(a) is a copy of a portion of a seismogram of a local earthquake written by this instrument with a 0.1-second-period galvanometer. Figure 1(b) shows a portion of a seismogram of a teleseism written with the same galvanometer.

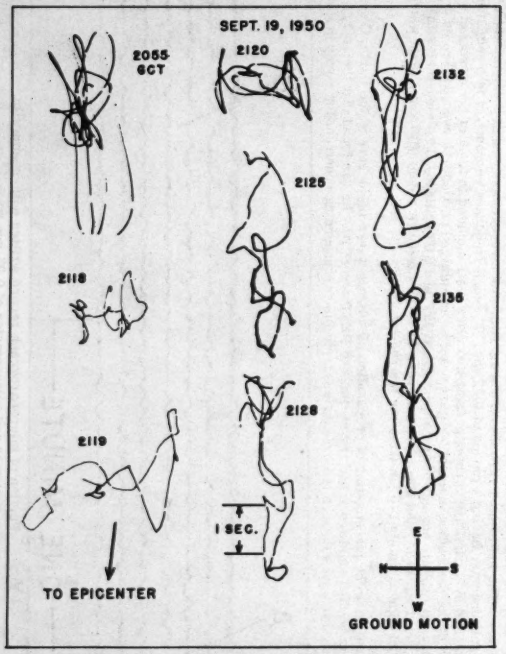


Fig. 4--Vector seismograms of selected wave-groups of earthquake of September 19, 1950 near $\phi = 2°N$, $\lambda = 138.5°E$

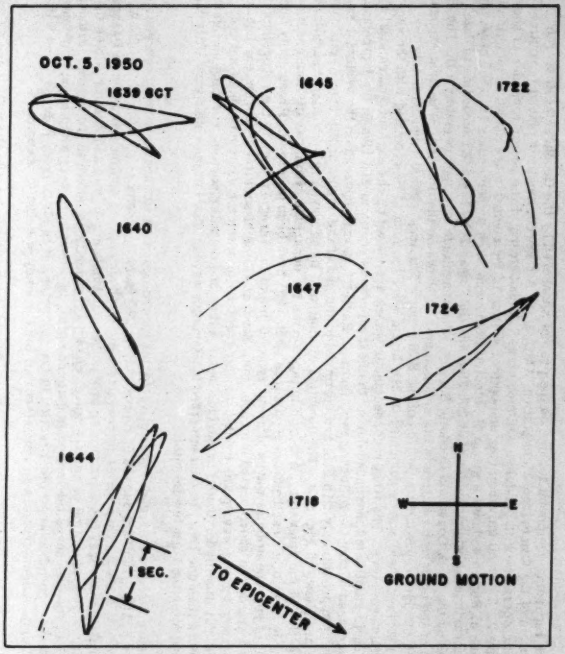


Fig. 5--Vector seismograms of selected wave-groups of earthquake of October 5, 1950 near $\phi = 10.5°N$, $\lambda = 85°W$

The recording equipment for use on the project sponsored by the Geophysical Research Directorate of the Cambridge Field Station, AMC, U. S. Air Force, has been placed in routine automatic operation with pendulum seismometers. A photograph of the vector recorder is shown in Figure 2. The dual galvanometer and optical system of the recorder are shown schematically in Figure 3. Figure 4 shows a group of selected exposures taken on September 19, 1950 of waves from an earthquake which occurred at 20h 29m 48s GCT near 2°N, 138.5°E, according to data supplied by the U. S. Coast and Geodetic Survey. The magnitude was approximately 7.0. The direction of the epicenter relative to the seismometer is shown on the drawing. The first exposure taken at 20h 55m represents a portion of the SKS group. The long-period (approximately one minute) surface shear waves beginning at 21h 11.2m were too long to be recorded with the vectorial galvanometers. The first recorded shear waves are shown on the exposure taken at 21h 18m. Their amplitudes increased during the next minute as shown at 21h 19m in the figure and then decreased during the following two minutes. Rayleigh waves appeared on the vectorial exposures at approximately 21h 21m and continued to the end of the series at 21h 55m. Four examples are shown in Figure 4. The direction of motion of these waves is very nearly parallel to the direction of the epicenter. Although in this series the departures from parallelism are small, in records from other earthquakes departures up to $\pm 15°$ have been observed. Presumably this is a result of superposition of waves of shear type. Some of the irregularities in the recordings of Figure 4 are due to short-period microseisms. Several series of such records from earthquakes having trans-Pacific wave paths exhibit similar patterns in which the early portion of several minutes' duration is dominated by surface shear waves and the later portion, covering an interval up to more than one hour, is characterized by Rayleigh waves. The latter exhibit very little change in period after the first few minutes.

Figure 5 shows enlarged copies of vectorial recordings of an earthquake which occurred October 5, 1950, 16h 09m 34s GCT, approximately 37° from Pasadena at $\phi = 10.5°N$, $\lambda = 85°W$, magnitude = 7 3/4 +. This series is characteristic of shocks having continental paths to Pasadena. The long-period waves began recording at Pasadena at 16h 26m. In this and similar series the direction of ground motion of surface waves changes frequently as shown in the figure. Although in some of the exposures the motion is quite complex, in others it is very simple and is oriented parallel or perpendicular to the direction of the epicenter. It is clear from Figures 4 and 5 that the vectorial seismograph is an important tool for the study of seismic phenomena.

A microbarograph with moving conductor electromagnetic transducer [BENIOFF and GUTENBERG, 1939] has been modified by Benioff and is in continuous operation at the Seismological Laboratory. The instrument records on 35-mm film with a recording speed of 0.25 mm/sec and with a galvanometer having a period of 0.25 sec. The high-frequency response of this combination is controlled by a capillary opening passing through a plate mounted in front of the moving diaphragm of the responding element. Figure 6 shows an enlarged portion of a record taken on a quiet day. It exhibits normal microbaroms [BENIOFF and GUTENBERG, 1939] together with direct sound waves (A) and about 1 1/2 minutes later stratosphere waves (B) from a blast which occurred approximately 140 km from the instrument.

Continuing the investigation of propagation of seismic waves in the core of the Earth, Gutenberg has studied amplitudes and travel times of PKKP and P′P′. He has found that the energy spectrum for waves through the core differs from the corresponding spectrum for waves passing

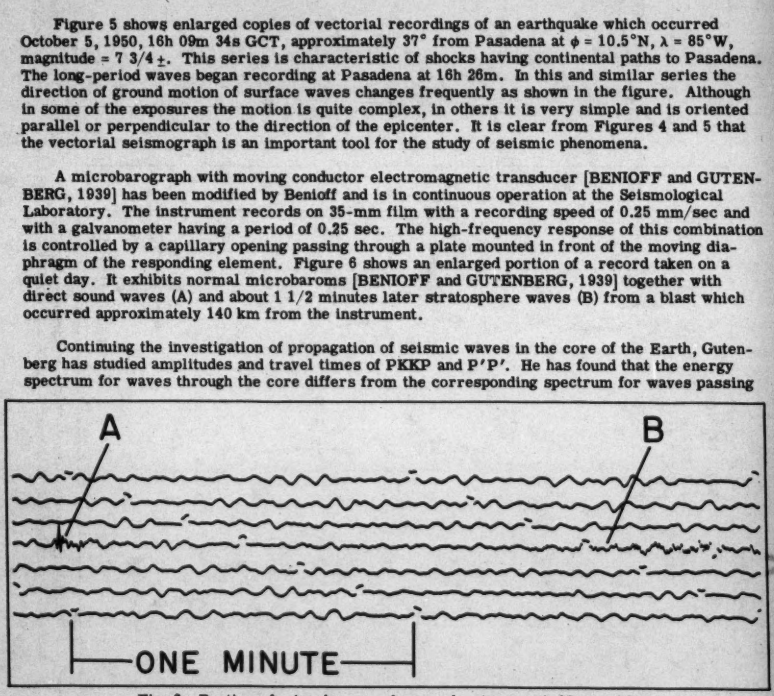


Fig. 6--Portion of microbarograph record written with 35-mm film recorder and galvanometer of 0.25-sec period

only through the mantle. Waves with periods over four seconds exhibit relatively small amplitudes in P′ and P′P′; PKKP waves with periods of more than three seconds are rare. In agreement with theoretical expectation PKKP through the inner core is usually not observed. The fact that PKKP through the outer part of the core is well observed indicates a ratio of probably at least 1.7 for the densities inside and outside the outer core. At the boundary of the inner core (radius about 1300 km) the velocity increases from about ten to about 11 km/sec within roughly 100 km and is about 11.2 km/sec in most of the inner core. No indication of a decrease in velocity with depth near the inner core could be found. P″ at distances between its beginning near 105° and a distance of about 125° is probably mainly due to waves reflected externally at the boundary of the inner core.

In a further investigation on waves reflected at the core, K. Ergin found that the abnormal ratios of horizontal to vertical components reported previously result from the fact that the horizontal and vertical component maxima in PcP, ScP, PcS, and ScS are not simultaneous. A possible cause of the minor component (perpendicular to the direction of the expected motion) is transformation between longitudinal and transverse waves at discontinuities in the crust.

Determinations of magnitudes and locations of epicenters of earthquakes supplementary to "Seismicity of the Earth" have been carried forward by Gutenberg and Richter.

Our station at Crestline was destroyed by fire on August 31, 1950. The instruments formerly at Pomona College have been moved to Dalton ($\phi = 34° 10.2'$N, $\lambda = 117° 48.6'$W, $h = 523$ meters). This station is at the Big Dalton Dam of the Los Angeles County Flood Control District. We are much indebted to the officials and personnel of the District for providing adequate housing and maintenance.

The station at China Lake has been placed on a permanent basis with excellent cooperation from officers and personnel of the Naval Ordnance Test Station at Inyokern. A new seismometer vault and recording-room have been provided. A short-period Benioff vertical-component seismograph with paper recorder is operating at its maximum available sensitivity. A film recorder has been modified by F. E. Lehner to accommodate a long-period galvanometer for use with the same vertical seismometer. This instrument has been operating satisfactorily under test and is now ready for installation at China Lake.

Markus Båth of the University of Uppsala arrived in October 1950 for several months of study and research in seismology.

Gutenberg attended a conference concerning the evolution of the Earth which was held from January 22 to 25, 1950 at Rancho Santa Fe, California.

Gutenberg and Benioff participated in a Colloquium at Hershey, Pennsylvania, September 12 to 14, 1950 on plastic flow and deformation within the Earth. They are members of the committee editing its proceedings.

On February 28, 1951 an unusually large shock at intermediate depth (magnitude 7 3/4) occurred off Hokkaido. On August 15, 1950 there was a very large shallow shock in southeastern Tibet, for which the preliminary magnitude is 8.6. There was extraordinarily high activity during the first half of December 1950, including the following large shocks (magnitudes mostly 7 3/4 to 8): December 2, New Hebrides; December 9, Chile; December 10, Kermadec Islands; December 14, Tonga Islands; December 14, Mexico. The last four of these were at intermediate depth. Even without the shock in February, they represent the greatest release of seismic energy at intermediate depth in any year since 1903, when adequate instrumental data first began to be available.

The shock on December 2, at a depth of about 40 km, had an unusually long series of recorded aftershocks. This is being investigated by Benioff.

An exceptional swarm of shocks of magnitudes up to 5 1/2 originated in the northern Imperial Valley near Calipatria and Niland from July 27 to August 1.

The following Laboratory publications appeared during 1950:

Benioff, H., B. Gutenberg, and C. F. Richter, Progress report, Seismological Laboratory, California Institute of Technology, 1949, Trans. Amer. Geophys. Union, v. 31, pp. 463-467, 1950.

Gutenberg, B., Structure of the Earth's crust in the continents, Science, v. 3, no. 2872, pp. 29-30, 1950.

Gutenberg, B., Earthquakes in North America, Science, v. 3, no. 2883, pp. 319-324, 1950.

Gutenberg, B., and C. F. Richter, Géographie des tremblements de terre et dynamique de la croûte terrestre, Ann. Institut de Physique du Globe de Strasbourg, v. 5, 11 pp., 1950.

Martner, S. T., Observations on seismic waves reflected at the core boundary of the Earth, Bull. Seis. Soc. Amer., v. 40, pp. 95-109, 1950.

Richter, C. F., History and applications of the magnitude scale, Publications du Bureau Central Séismologique International, Serie A, Travaux Scientifiques, Fasc. 17, pp. 217-224, 1950.

Richter, C. F., Velocities of P at short distances, Bull. Seis. Soc. Amer., v. 40, pp. 281-289, 1950.

References

BENIOFF, H., and B. GUTENBERG, Waves and currents recorded by electromagnetic barographs, Bull. Amer. Met. Soc., v. 20, pp. 422-426, 1939.

Seismological Laboratory,
California Institute of Technology,
Pasadena, California

(Manuscript received January 23, 1951; presented at the Thirty-Second Annual Meeting, Washington, D. C., April 30, 1951; open for formal discussion until March 1, 1952.)

Transactions, American Geophysical Union Volume 32, Number 5 October 1951

REPORT OF THE STANDING COMMITTEE ON PROBLEMS OF THE UPPER ATMOSPHERE

W. W. Kellogg, Chairman

A. P. Crary
Michael Ference
J. Kaplan
A. G. McNish
F. E. Roach
Lyman Spitzer, Jr.
J. A. Van Allen
Fred L. Whipple
Oliver R. Wulf

This is the first report of the new Standing Committee on Problems of the Upper Atmosphere of the Section of Meteorology, AGU. It is intended that this report be primarily of use to those who are not specialists in the upper atmosphere, but it is probable that it will be of use to people working in this field also, since it is becoming difficult to keep up with the recent developments.

The phases which are being specifically discussed below are upper-atmosphere research by means of sound-propagation observations and by means of meteor observations, and research on some of the theoretical aspects of the upper atmosphere. It is recognized that this leaves some serious gaps, such as ionospheric research by radio-radar techniques, soundings by rockets, and studies of the radiations from the upper atmosphere. An attempt will be made to fill these gaps in future reports, since it is hoped to make one every year.

Sound propagation studies (A. P. Crary, Geophysical Research Directorate, Air Force Cambridge Research Laboratories)--The Air Force Cambridge Research Laboratories are currently determining winds and temperatures in the 30- to 60-km level by studies of compressional waves generated by explosions, and refracted back from the high temperature layers of the middle stratosphere. The separation of the variation of the sonic velocity into its two major components, winds and temperatures, is made possible by measuring the velocity of the acoustical wave along various azimuths. The main phases of the work have been the studies of the diurnal, seasonal, and latitudinal variations. Results to date have indicated: (a) no appreciable diurnal variations in the stratosphere; (b) east winds up to 50 to 75 m/sec during the summer months with minimum values in the high latitudes; (c) general west winds up to 50 to 75 m/sec during the winter months with minimum values in the tropical latitudes; (d) temperatures which reach a maximum value, close to ground temperature, at 50 to 55 km, with lower values of the maximum in Arctic winter and over oceanic areas [CRARY, 1950].

Upper-atmosphere acoustical studies have been reported recently in England by Murgatroyd, in India by Mathur, and in this country by Cox during observations of large explosions at Arco, Nevada, and at Helgoland. Acoustical studies are currently in progress, under contract to the Air Force Cambridge Research Laboratories, at the University of Denver and at the University of Alaska, with continual data being gathered to determine the annual variations at these sites.

The Air Force Cambridge Research Laboratories plan to conduct acoustical studies by a network of five sites in the middle and lower latitudes off the eastern coast of the United States during June and July 1951.

Meteor observations and their interpretation (Fred L. Whipple, Harvard College Observatory)--The study of the upper atmosphere by means of meteors has been conducted by three general techniques of observation: visual, radio-radar, and photographic. In recent years the visual techniques for the direct observations of meteors have ceased to constitute a primary observational technique, except to a limited extent for the study of the motions of the persistent luminous trains. They have served chiefly as an adjunct to observations by radio or photographic techniques. Because of the greater precision attainable by the radio and photographic techniques, we may expect that in the future almost all upper-atmospheric research by means of meteors will be conducted with the two latter methods.

A meteor is a phenomenon in the upper atmosphere arising from the interaction of a fast-moving solid particle, a meteoroid, with the atmosphere. The velocities range from a minimum of 11.3 km/sec, free fall from infinity, to a maximum of about 72 km/sec, arising from a head-on encounter with the Earth of a body in a closed orbit about the Sun. No evidence for bodies entering the solar system from interstellar space has been indicated by the photographic meteor work at

Harvard or the radio-radar studies by P. M. Millman and D. W. R. McKinley at Ottawa, Canada, and by A. C. B. Lovell and his colleagues at Manchester, England. The general dimensions of the meteoroids involved in these studies are of the order of one cm radius for the photographic meteors to perhaps one mm in radius for the faintest observed by radio techniques. The luminosity in a meteor arises from the interaction of material vaporized from the surface of the meteoroid with the atmosphere, giving a spectrum only of the constituents of the meteor. Observed are the lines of the neutral atoms Fe, Na, Ca, Mg, Mn, Cr, Ni, the ionized atoms Ca, Mg, and Si, and possibly bands of FeO. No spectral components definitely assignable to atmospheric constituents have been observed.

Little is known about the detailed production and energy-storing mechanism for the persistent luminous trains left by meteors. Recently P. M. Millman has photographed the spectrum of a train within about 0.01 second after the meteor; it showed low excitation lines of neutral elements. For extremely large meteoroids the train will sometimes persist for a number of minutes, although the persistence for ordinary visual meteors is a few seconds or less; considerable data on correlations of luminous trains with velocity and brightness have been compiled by P. M. Millman and J. A. Robins recently.

The observed distortions of trains indicate rapid systematic and turbulent motions in the upper atmosphere. A compilation of observations of some 1500 trains by C. P. Olivier indicates that the average wind velocity is 203 km/hr for night trains at a mean height of around 90 km, and 182 km/hr and 173 km/hr respectively for daylight or twilight trains in a total altitude range from 77 to 27 km. The directions of motions of the chief winds so determined probably vary with latitude and season, if not generally with geographical position, but such correlations have not been well determined.

Radio measures of upper-atmospheric winds have been made by L. A. Manning and O. S. Villard of Stanford University, utilizing the "body-Doppler" motion of the ionized columns left by meteors. Their observations, made in the early morning hours, indicate wind velocities from 46 to 200 km/hr, with a predominant direction towards NNE, but with a number of motions oppositely directed. There is, however, some question of interpretation of the Doppler motions of the ion trains observed by radio techniques. In particular, there tends to be a systematic retrograde motion in all available directions. This has caused the Manchester group in England some hesitation in interpreting the body-Doppler effect directly in terms of wind motion in the upper atmosphere. Undoubtedly this uncertainty will be clarified in the near future.

In the long run it appears that the radio techniques should be the most generally useful for synoptic studies of wind velocities, at least in the general altitude range of the E-layer and possibly somewhat below these altitudes. However, preliminary experiments in photographing persistent trains have met with success at Harvard. It is believed that a program conducted with the Super-Schmidt meteor cameras now under construction will prove fruitful in the precise determination of wind velocities over a considerable altitude range, and will provide precise absolute calibration for other methods of wind determination.

Radio-radar techniques for the observations of the ion trails accompanying and behind the meteoroid have been developed and used by a number of groups, particularly the Manchester, England, group under the direction of A. C. B. Lovell, the Canadian group of the National Research Council under the direction of D. W. R. McKinley and aided by P. M. Millman, the Stanford University group under L. A. Manning and O. S. Villard, and the National Bureau of Standards group under the direction of A. G. McNish. These various researches have contributed markedly to the observational material concerning the reaction of meteoroids with the atmosphere, but to date the observations have not been completely enough interpreted to provide much information concerning the upper atmosphere itself. The radio-radar techniques for the observations of meteors must be considered as extremely powerful tools for analysis of the upper atmosphere, but at the moment as too new and undeveloped theoretically to have provided much basic data or understanding.

The photographic techniques for the observations of meteors have been utilized largely at the Harvard College Observatory and in recent years have been assisted by a contract with the U. S. Naval Bureau of Ordnance. Wide-angle cameras equipped with rotating shutters controlled by synchronous motors have been used for the primary photography. These cameras, when operated in pairs at stations separated by the order of 30 km, provide for each meteor the precise trajectory, the brightness and brightness variations of the meteor with time, the velocity of the meteoroid, and, in most cases, measures of its deceleration by atmospheric resistance.

A theory for the determination of atmospheric densities from such meteor observations has been developed by the writer and utilized for the last dozen years. The range in heights within

which such measurements can be made extends from about 45 to 120 km. The most numerous and precise determinations are made in the range from about 65 to 95 km. The dimension of the meteoroid is determined essentially by a theory of the luminous efficiency, coupled with observations of intensity (and calibrated by actual density determinations in the region below 65 km). In the best determinations the air density is determined by the drag on the meteoroid produced by the atmosphere.

In recent years a clear-cut seasonal variation in the density of the upper atmosphere in the region from 70 to 90 km has been demonstrated by atmospheric densities determined from the photographic meteors at Harvard. The work of F. L. Whipple, L. Jacchia, and Z. Kopal indicates that the total amplitude is of the order of 0.4 in $\log_{10} \rho$, and that the phases of maximum and minimum density in the upper atmosphere are coincident respectively with the maximum and minimum ground temperatures. No correlations with other phenomena have been indicated definitely. From more extensive observations L. Jacchia has shown that the seasonal range tends to decrease with altitude, the maximum being reached in the neighborhood of altitude 70 km. H. Wexler has shown that such a variation of ρ must correspond to a mean stratosphere temperature which is higher in summer than in winter.

In recent years some question concerning the validity of the density determinations made by the photographic meteor techniques has arisen because of a discrepancy between density determinations by this method and those made by rockets. Although the meteor and rocket observations agree in the slope of the density-height or temperature-height relationships in the 70-km region, they diverge above this region, in the sense that the meteor observations indicate higher densities by approximately a factor of three at an altitude of about 90 km. It must be borne in mind in assessing this divergence that the meteor observations were made over the general area of Boston, Massachusetts, latitude 42.5°N, while the rocket results were obtained over Las Cruces, New Mexico, latitude 32.5°N. Recent unpublished reductions by L. Jacchia of meteors photographed above the region of Las Cruces indicate that densities measured at this locality by the meteor technique are in substantial agreement with the rocket measures. It appears very likely, then, that the apparent discrepancy arises from a true variation in the mean density of the upper atmosphere, depending upon geographical position. The sense of the variation is an increase in upper atmospheric density (and temperature) at between 70 and 90 km with increasing latitude over the middle latitudes considered. This conclusion demands further investigation, both observational and theoretical.

The general question as to whether meteors contribute enough energy to account for an appreciable fraction of the nocturnal ionization in the region of the E-layer is still not definitely settled. The consensus of opinion, however, leans heavily toward the conclusion that contributions by meteors to the general nocturnal ionization must generally be trivial compared to the observed ionization. It is possible, on the other hand, that the meteoroids do contribute appreciable material that produces observable night-sky effects such as the twilight air glow of Na. It is also possible that the micro-meteorites may contribute a measurable amount of daylight scattering in the upper atmosphere. E. Öpik and F. L. Whipple have shown that sufficiently small bodies entering the Earth's atmosphere at relatively low velocities may radiate away the energy produced by their encounter with the atmosphere rapidly enough that they are not vaporized. Hence these small bodies will settle slowly through the atmosphere as potential scatterers of sunlight. The quantities of such small particles in the upper atmosphere should eventually be measured directly by the following techniques, which have been developed but not yet fully exploited:

(1) Pitting of polished surfaces on rockets, as studied by T. R. Burnight of the U. S. Naval Research Laboratory.

(2) Sounds produced by micro-meteorites encountering a high-altitude rocket, as measured by J. L. Bohn of Temple University in conjunction with the U. S. Air Materiel Command rocket researches.

(3) The collection of atmospheric dust by aircraft in "clean" volumes of the atmosphere, as developed by W. D. Crozier and B. K. Seely of the New Mexico School of Mines.

From the varied aspects of the above discussion it is apparent that meteoric bodies reacting with the high-level regions of the atmosphere have become, and will remain, important contributors to our knowledge of the upper atmosphere.

Theoretical studies of the ionosphere and exosphere (Lyman Spitzer, Jr., Princeton University Observatory)--This complex and important subject has received considerable attention in the last few years. Since the theoretical interpretation of ionospheric processes is still in a state of flux, it will suffice to refer here to two groups of papers that seem to represent particularly important advances in this field.

In a number of papers by R. Penndorf the vertical distribution of atomic oxygen has been calculated, using new data of ultraviolet solar radiation. The influence of zenith distance of the Sun, the uncertainty of the rate constant of the three-body recombination process, and the variation between day and night conditions are worked out. The transition layer between molecular O_2 and atomic O occurs around 100 to 110 km, and its thickness is about ten km. The height of the transition layer does not change during the night [PENNDORF, 1949]. The vertical distribution of densities of O, O_2, and N_2 are given by PENNDORF [1950b] and the energy absorbed around the E-layer by PENNDORF [1950a].

Significant advances in atmospheric physics have been made by D. R. Bates and his co-workers. The present state of our knowledge (and lack of knowledge) concerning the formation of each of the ionospheric layers has been reviewed in detail [BATES and SEATON, 1950]. Analytical studies of the negative-ion concentration in the D- and E-layers show that, even with the most extreme assumptions, the electrical conductivity is less than the value required by current theories of the variations observed in the geomagnetic field [BATES and MASSEY, in press].

The temperature of the atmosphere in the F-layer and above has also been discussed by BATES [in press]. The main radiative cooling process is found to be the emission of photons by the magnetic dipole connecting the two low levels of the ground term of atomic oxygen; the main non-radiative process is thermal conduction. These two are so effective that it would seem that the extreme ultra-violet emission of the Sun must be well in excess of that from a 6000° K black body if the region concerned is really at a high temperature.

Theoretical studies of the relationships between the upper atmospheric circulations and the geomagnetic field (Oliver R. Wulf, U. S. Weather Bureau)--It is generally agreed that there is an interaction between the Earth's magnetic field and the motions of the air in the ionosphere. In particular, there seems to be a chain of cause and effect by which changes in solar activity result in changes in the geomagnetic field through the intermediary of the upper atmosphere, though the details of this complicated process are far from clear.

In an effort to identify further solar features associated with geomagnetic activity, attention has been called to instances in which an area of bright chromospheric clouds was observed to come around the east limb of the Sun, because of solar rotation, at about the time of onset of particularly well-defined periods of multiple-recurrent geomagnetic activity. The development in time of such geomagnetic activity has been studied, and it is believed that the relatively abrupt onset after rather quiet days followed by a more gradual dying away of activity is suggestive of a process involving the precipitation of an accumulated instability of some kind, which in the atmosphere could be instability of air flow. It is suggested that the absorption of a relatively abrupt increase of solar ultraviolet radiation in the upper atmosphere of the Earth could be the cause of such a change. Since the dynamo theory of the daily variation of the Earth's magnetic field implies that all large-scale air motions in the electrically conducting region should in some measure affect the Earth's field, irregular air motions there resulting from such instability should, from the point of view of this theory, also affect the field, and should produce at least a part of the geomagnetic disturbance.

It has been demonstrated that there is a tendency for some prominent multiple-recurrent geomagnetic activity to occur at times of high lunar declination, and a suggestion has been made as to how this might be caused by the declination component of the lunar air tide. Such a tendency would imply a very weak true periodicity superposed on the well-known 27-day quasi-periodicity in geomagnetic activity [WULF and NICHOLSON, 1948abc, 1950].

In a study made of certain well-defined features of geomagnetic data together with the character of the large-scale atmospheric circulation as known to the heights of sounding balloons, evidence was adduced indicating that these may be interrelated. This suggests that a detailed extension of such a study could lead to an explanation of some conspicuous features of the geomagnetic variations in terms of the atmospheric circulation, and also to a way of deducing certain large-scale features of the atmospheric circulation from current magnetic observation [WULF and HODGE, 1950].

References

BATES, D. R., and M. J. SEATON, Theoretical considerations regarding the formation of the ionized layers, Proc. Phys. Soc., B, v. 63, pp. 129-140, 1950.

BATES, D. R., Proc. Phys. Soc., B (in press).

BATES, D. R., and H. S. W. MASSEY, J. Atmos. and Terr. Phys. (in press).

CRARY, A. P., Stratosphere winds and temperatures from acoustical propagation studies, J. Met., v. 7, pp. 233-242, 1950.

PENNDORF, R., The vertical distribution of atomic oxygen in the upper atmosphere, J. Geophys. Res., v. 54, pp. 7-38, 1949.

PENNDORF, R., Absorption of solar energy by oxygen molecules in the E-layer, J. Met., v. 7, pp. 243-244, 1950a.

PENNDORF, R., The distribution of atomic and molecular oxygen in the upper atmosphere, Phys. Rev., v. 77, pp. 561-562, 1950b.

WULF, O. R., and SETH B. NICHOLSON, A possible influence of the moon on recurrent geomagnetic activity, Phys. Rev., v. 73, pp. 1204-1205, 1948a.

WULF, O. R., and SETH B. NICHOLSON, On the identification of the solar M-regions associated with terrestrial magnetic activity, Pub. Astron. Soc. Pacific, v. 60, pp. 37-53, 1948b.

WULF, O. R., and SETH B. NICHOLSON, Recurrent geomagnetic activity and lunar declination, Pub. Astron. Soc. Pacific, v. 60, pp. 259-262, 1948c.

WULF, O. R., and SETH B. NICHOLSON, Solar flares and moderate geomagnetic activity, Pub. Astron. Soc. Pacific, v. 62, pp. 202-210, 1950.

WULF, O. R., and MARY W. HODGE, On the relation between variations in the Earth's magnetic field and variations of the large-scale atmospheric circulation, J. Geophys. Res., v. 55, pp. 1-20, 1950.

Institute of Geophysics (W.W.K.),
University of California,
Los Angeles, California

(Communicated manuscript received April 20, 1951;
open for formal discussion until March 1, 1952.)

Transactions, American Geophysical Union Volume 32, Number 5 October 1951

REPORT OF THE COMMITTEE ON CLOUD PHYSICS--1951

Horace R. Byers, Chairman

Charles E. Anderson
George S. Benton
Roscoe R. Braham, Jr.
Ferguson Hall
Helmuth Weickmann

Since the first experiments in November 1946 by Vincent J. Schaefer in modifying natural, supercooled clouds with so-called seeding agents, the fascinating subject of artificial nucleation has dominated the thinking in cloud physics throughout the world. Although relatively little has been published on the subject, information about it has spread rapidly through the public press. It is therefore assumed that all to whom this report is addressed are familiar with the general aspects of the subject. This Committee will confine itself to reviewing the more recent developments and reporting on the present status of the research as revealed in published scientific papers.

The review of recent contributions will be divided into two parts: (1) a survey of the work directly concerned with artificial nucleation in the atmosphere; (2) papers on fundamental problems of cloud physics, with emphasis on those results which bear a close relationship to cloud-modification studies.

Applied research--Seven papers or groups of papers will be mentioned here as important landmarks in the application of seeding techniques during the past year. They are (1) a report by C. E. Anderson on results of the joint Air Force - Weather Bureau cloud-seeding trials; (2) two articles by Vonnegut discussing the details of the use of silver iodide; (3) an article in Science by Langmuir describing striking rain-making results in New Mexico, and a critical communication about it by Ferguson Hall and others in a later issue of the same journal; (4) the discovery by Langmuir of a seven-day periodicity in weather ascribed to periodicity in distant seeding operations, and a published challenge to these conclusions by a committee of the American Meteorological Society; (5) publication of results of a symposium on the subject by the New York Academy of Sciences; (6) announcement by Reynolds, Hume, Vonnegut, and Schaefer that nucleation activity of silver iodide is markedly reduced by exposure to sunlight; (7) a paper by H. G. Houghton offering reasons for discounting claims of significant precipitation amounts or large-scale effects due to seeding.

Specific references to these papers may be found at the end of this report. They now will be discussed in order.

(1) ANDERSON's [1950] evaluation of the results of the Air Force - Weather Bureau cloud-seeding trials of 1949 brought out a number of factors about mechanisms in the freezing portions of clouds which previously had received little attention. These included alternative computations of the number of nuclei produced by carbon-dioxide pellets, and the introduction of strong observational evidence that graupel particles are primarily responsible for rains in middle-latitude regions of the Earth. Results of seeding in the Sierra Nevada region showed that holes in supercooled altocumulus layers could be created by seeding provided the layers were less than 1000 ft thick and general horizontal divergence existed below. The tests in the Gulf Coast region combined with previous trials led to the conclusion: "The chance of initiating precipitation (although virga only) is excellent in building cumulus containing supercooled drops only. The chance of success of partially dissipating the subject cloud would seem even greater, since this condition ensued in 100 pct of the trials."

(2) VONNEGUT's [1950ab] two papers on silver-iodide smoke covered (1) the design and use of silver-iodide smoke generators, the details of which will not be dwelt upon here; (2) some of the results of seeding of stratified clouds. The modification of supercooled stratified layers has been the most striking and clearly substantiated of all cloud-seeding effects. Remarkable aerial photographs showed large areas where silver-iodide nuclei distributed from an airplane had changed the supercooled layer to an ice-crystal layer. In this new form the cloud particles apparently began to precipitate and often evaporated to make an opening in the seeded part of the

layer. A special photographic technique for clear identification and measurement of the modified areas was developed.

(3) A large development of thunderstorms and heavy rains occurred on October 14, 1948 and July 21, 1949 in parts of New Mexico where Langmuir and co-workers had carried out seeding operations with silver iodide. After a number of enthusiastic discussions of the results at scientific and other meetings, LANGMUIR [1950a] published them. In order to demonstrate that the rain was caused by the seeding and had not developed naturally and coincidentally, Langmuir computed the probability of the observed rainfall patterns having occurred as a result of natural causes. The computed probability was so low that Langmuir concluded the storms could not have resulted except from the seeding. The results of these experiments, as interpreted, were so striking that the future of rainmaking might be expected to rest on their acceptance. Criticisms were forthcoming [HALL and Others, 1951] in a subsequent issue of Science. Ferguson Hall questioned Langmuir's probability figures, asserting that they were based on treatment of rainfall values in subareas of New Mexico as so many independent random numbers, which is not permissible for meteorological phenomena. He then proceeded to examine the rainfall situation on July 21, one of the dates in question, to show that thunderstorms and rain showers were occurring throughout the state and in surrounding areas far beyond the limit of drift of the silver iodide and that therefore it was possible for the rain to have occurred naturally.

(4) The attribution of weather periodicities in the Middle West to systematic release of silver iodide in New Mexico created a sensation in the scientific world. Now the effects of artificial nucleation were carried beyond the local modification of clouds and rainfall patterns to include major disturbances of the atmosphere. This seemed to imply that the physical basis for the study of great circulations in the atmosphere was incomplete because it did not take into consideration the distribution of sublimation nuclei, that this was perhaps the most important factor of all, and that it could be controlled easily. These interpretations were so challenging that they drew a barrage of fire from critics even before a summary was published by LANGMUIR [1950b] and discussed by HAURWITZ and Others [1950].

LANGMUIR [1950b] discovered that during April and other periods of 1950 there was a seven-day period clearly marked in the rainfall of a large area in the Mississippi Valley. At the same time silver iodide was being released at certain times each week at the New Mexico School of Mines, Socorro, New Mexico. Because of the unusualness of the periodicity and the heavy rainfall in the region the two events appeared to be connected. Seeding seemed to be causing large storms and major disturbances in the general circulation of the atmosphere. Before this, the American Meteorological Society, aroused by reports appearing in newspapers and Project Cirrus reports to the Department of Defense, appointed a Special Committee to evaluate the theory and results. The Committee's report, published in the Bulletin and in Science, although stated in general terms, found no basis for acceptance of the Langmuir thesis. The Committee stated, in part: ". . . the patterns of weather and rainfall over the United States during this period were quite similar to a number of corresponding periods in the past, and . . . they fit very naturally and normally into the rather unusual Northern Hemisphere weather pattern of that period." The Committee advocated a carefully designed test of all cloud-seeding effects.

(5) On May 23, 1950, the Section of Oceanography and Meteorology of the New York Academy of Sciences held a symposium on "Induced precipitation." Four papers were presented, by Wallace E. Howell, SCHAEFER [1950], LEWIS [1950], and PIERSON [1950]. (Howell's paper was not published.) Schaefer outlined the progress made in inducing precipitation and discussed the ways in which further experimentation may bring important results. Possibilities of creating cloud-shadow by inducing extensive areas of "false" cirrus were mentioned. Lewis' paper brought out factors which apparently had not received enough attention, such as the time required for ice formation in supercooled clouds and the distinction between vertically developed and layer clouds in this regard. He stated the view that the distribution of precipitation is determined primarily by air circulation rather than nuclei. Pierson's paper related cloud seeding to the large-scale factors of time and space to show that the meteorological processes of air trajectory and atmospheric stratification cannot be ignored.

(6) REYNOLDS, HUME, VONNEGUT, and SCHAEFER [1951] published a brief note reporting that silver iodide was photosensitive and that in the presence of sunlight its potential activity as a sublimation or freezing nucleus was reduced by two orders of magnitude (99 pct) in the first hour. The reader would interpret this finding as casting doubt on some of the long-period effects of that seeding agent. This was indeed an important discovery and has no doubt led experimenters to try to find a better, more stable seeding chemical.

(7) HOUGHTON's [1951] appraisal can best be described by quoting directly his abstract: "The results of cloud-seeding experiments are reviewed briefly and it is concluded that, taken alone, they do not constitute an adequate basis for a sound appraisal of the potentialities of the cloud-seeding techniques. An attempt is made to extend and supplement the observational evidence with the aid of existing knowledge of cloud physics and synoptic meteorology. It is found that significant amounts of precipitation can fall only from clouds which are continuously replenished. It is concluded that the thermal effects of seeding are seldom sufficient to stimulate the vertical development of a cloud. Since the activation temperatures of the artificial ice nuclei are believed to be higher than the activation-temperatures of natural ice nuclei, there is a possibility that seeding may advance the onset of precipitation or release precipitation from clouds which do not extend to the activation temperature of the natural ice nuclei. It appears that the seeding of clouds which are already releasing precipitation may either decrease or increase the total precipitation; an unequivocal answer is not possible due to the lack of pertinent information regarding natural precipitation processes. On the basis of the analysis of the physical processes and general knowledge of synoptic meteorology, it is concluded that it is unlikely that cloud seeding will cause large-scale effects. Further research on cloud physics and cloud seeding is recommended."

In summarizing the practical applications, this Committee notes that while all writers appear agreed on the idea that clouds can be modified by artificial nucleation, there is wide disagreement on the economic importance of these effects, particularly with regard to rainfall and large-scale modifications of the atmospheric circulation. The Committee does not deplore this disagreement but believes it is a sign of healthy scientific growth in a facet of science where controlled experiment is almost impossible. It expresses the hope that those concerned with this field will approach it with an open mind, with true scientific method, and with, above all, highest regard for the public welfare.

Fundamental research--Fundamental research seems essential in arriving at an early answer to the question of the ultimate possibilities of human manipulation of cloud systems. Although gross experiments in the artificial modification of precipitation may proceed more or less independently of basic investigations of natural precipitation processes, such experiments have two inherent weaknesses. First, the hypothesis on which present cloud-seeding experiments are conducted is based on assumptions regarding natural precipitation processes, and the probable occurrence in nature of the conditions required by such processes. Some of these assumptions are still in the process of being substantiated. Secondly, actual experiments in cloud seeding often fail to furnish definitive results because it is hard to separate out the natural variability of precipitation, whether from individual clouds or in areal precipitation.

Recent basic cloud-physics research has been mainly along two lines: (1) attempts to evaluate the relative importance of the Bergeron-Findeisen ice-particle theory of precipitation with that based on collision and coalescence of cloud elements; and (2) explanations of the source of ice particles in the supercooled portions of clouds.

In a very illuminating article, BOWEN [1951] (Commonwealth Scientific and Industrial Research Organization, Sydney, Australia) presents the results of certain radar and aircraft observations of rainfall made near Sydney under various synoptic conditions. Both ground-based and airborne radar were used, the sets operating on a ten-cm wavelength, and having antennae rotating in a vertical plane. Flight observations in the clouds accompanied all observations. The "bright band" near the freezing level was examined and the explanation offered by many others that it was caused by the melting of snowflakes appeared to be verified. Quite unexpectedly, however, a second bright band was often noted at about the -16°C level. Sometimes this band remained fixed, but more often it slowly sank and finally merged with the lower one, with a new upper band then forming, the cycle recurring at around 20-minute intervals. In shower-type clouds the bright bands were conspicuously absent, even though the clouds and radar echoes extended well above the freezing level. The explanation is offered that the bright bands accompany precipitation formed by the ice-crystal process. Where the upper band is absent, the ice crystals form by direct sublimation. When present, the upper band is caused by the freezing and subsequent rapid growth of cloud drops being lifted upwards. Where the bands are absent, only the collision process is operative.

HOUGHTON [1950] attempted an evaluation of the relative importance of the Bergeron-Findeisen and collision mechanisms, and concludes that in middle latitudes a combination of the two is probably required for substantial precipitation. In tropical zones, however, the collision process may afford an explanation of rain from "warm" clouds.

The formation of rain by the collision process alone, both in tropical and middle latitudes, has been considered by BOWEN [1950] and by LUDLAM [1951] (Imperial College of Science and Technology, London). Updrafts of certain magnitudes combined with prescribed drop-size distributions (including rather large drops) are shown theoretically to permit growth to precipitation size.

Regarding the formation of ice particles in portions of clouds below freezing, MASON [1950] (Imperial College of Science and Technology, London) offers the tentative explanation that between temperatures of 0° and -32°C freezing of drops is caused by solid insoluble particles which are wetted by water and produce ice particles through the freezing of water drops. Between -32° and -41° nuclei are formed by the freezing of droplets of sea-salt solution, ice and salt crystallizing out on contaminating foreign particles at temperatures depending upon the efficiency of the particles and the rate of cooling. Below -41° they are produced by freezing of droplets of pure salt solution, and possibly by "gaseous" nuclei. Silver iodide is thought to act as a nucleus because of structural similarity to the ice crystal.

Further study of the size dependence of the freezing temperature of water drops was made by DORSCH and HACKER [1950] (Lewis Flight Propulsion Laboratory, Cleveland), and a further study of the data by LEVINE [1950] (same laboratory) indicated a fair degree of agreement between the data and that which would be expected if the probability of freezing by the action of "motes" were a function of drop volume.

An important discovery along a different line was that by WORKMAN and REYNOLDS [1950] (New Mexico School of Mines) that large electric potentials developed during the freezing of certain dilute solutions between the frozen and unfrozen portions. The mechanism was suggested as the source of thunderstorm potentials, and the possibility of modifying thunderstorms by injecting certain neutralizing chemicals was discussed.

REISS [1950] computed the half-lives of silver-iodide particles in supercooled water clouds. He refined Vonnegut's earlier data on the temperature dependence of these half-lives and showed that the temperature is extremely critical. The five-degree decrease in temperature from 253°K to 248°K transforms the half-life of particles of radius 0.8×10^{-6} cm "from what is almost an infinity to a virtual zero" (10^{520} to 10^{-38}). An extreme effect of particle radius is also computed. At 253°K an increase of radius from 0.8×10^{-6} cm to 10^{-6} cm also reduces the half-life from an infinity to zero (10^{520} to 5.6×10^{-4}).

WOODCOCK [1949, 1950] showed that large sea-salt nuclei are present over the Straits of Florida. These are of such weight (3 to 15×10^{-12} g) that they will form drops large enough to be classed as drizzle or light rain if a salt concentration within the drops of 70 mg per liter is assumed. In the clouds, at this concentration, an average of one cloud droplet per cm^3 would have a radius of 15 microns or more and would fall fast enough to grow by accretion. In another paper, the author reported measurements of sea-salt nuclei concentrations at various heights over the sea. In some cases the concentration of nuclei was very low, indicating that the assumption often made by meteorologists of plentiful salt nuclei universally present is not always justified.

KÖHLER [1950] presented a scholarly treatment of the subject of condensation nuclei introducing numerous refinements in the theory of condensation of atmospheric water vapor on nuclei.

A paper by LUDLAM [1950] indicated that the rate of loss of heat from ice particles growing by coagulation in dense supercooled clouds may be sufficient to allow all the acquired water to freeze. He further speculated that the large elements in cumulonimbus clouds may have a liquid outer layer at low temperatures (-20° or -30°C). This layer may tear off to form new drops, as envisaged by Langmuir for higher temperatures. It was estimated by the author that "splintering" in accordance with the Findeisen theory of electrical charge production in clouds, occurs only at temperatures below about -32°C because the particles would be wet at higher temperatures.

References

Applied research

ANDERSON, CHARLES E., Evaluation of results of Joint Air Force - Weather Bureau cloud-seeding trials conducted during winter and spring 1949, Geophysical Research Papers No. 4. Air Force, Cambridge Res. Lab., Cambridge, Mass., May 1950.

HALL, FERGUSON, and Others, Comments and communications - Dr. Langmuir's article on precipitation control, Science, v. 113, Feb. 16, 1951.

HAURWITZ, B., and Others, On the results of recent experiments in the artificial production of precipitation, Bull. Amer. Met. Soc., v. 31, pp. 346-347, Nov. 1950.
HOUGHTON, HENRY G., An appraisal of cloud seeding as a means of increasing precipitation, Bull. Amer. Met. Soc., v. 32, pp. 39-46, Feb. 1951.
LANGMUIR, IRVING, Control of precipitation from cumulus clouds by various seeding techniques, Science, v. 112, July 14, 1950a.
LANGMUIR, IRVING, A seven-day periodicity in weather in United States during April 1950, Bull. Amer. Met. Soc., v. 31, pp. 386-387, Dec. 1950b.
LEWIS, WILLIAM, The importance of artificial nucleation for the production of precipitation, Trans. New York Acad. Sci., ser. 2, v. 12, pp. 264-267, 1950.
PIERSON, WILLARD J., Jr., Large-scale control of weather by introduction of sublimation nuclei into the atmosphere, Trans. New York Acad. Sci., ser. 2, v. 12, pp. 268-270, 1950.
REYNOLDS, S. E., WILLIAM HUME, II, BERNARD VONNEGUT, and VINCENT J. SCHAEFER, Effect of sunlight on the action of silver iodide particles as sublimation nuclei, Bull. Amer. Met. Soc., v. 32, p. 47, Feb. 1951.
SCHAEFER, VINCENT J., Induced precipitation and experimental meteorology, Trans. New York Acad. Sci., ser. 2, v. 12, pp. 260-264, June 1950.
VONNEGUT, B., Techniques for generating silver iodide smoke, J. Colloid Sci., v. 5, pp. 37-38, 1950a.
VONNEGUT, B., Experiments with silver iodide smokes in the natural atmosphere, Bull. Amer. Met. Soc., v. 31, pp. 151-157, May 1950b.

Basic research

BOWEN, E. G., The formation of rain by coalescence, Australian J. Sci. Res., ser. A, Phys. Sci., v. 3, no. 2, pp. 193-213, June 1950.
BOWEN, E. G., Radar observations of rain and their relation to mechanisms of rain formation, J. Atmos. and Terr. Phys., v. 1, pp. 125-140, 1951.
DORSCH, ROBERT G., and PAUL T. HACKER, Photomicrographic investigation of spontaneous freezing temperatures of supercooled water droplets, NACA Tech. Note 2142, July 1950.
HOUGHTON, H. G., A preliminary quantitative analysis of precipitation mechanisms, J. Met., v. 7, pp. 363-369, 1950.
KÖHLER, H., On the problem of condensation in the atmosphere, Nova Acta, R. Soc. Scient. Upsaliensis, ser. 4, v. 14, no. 9, 1950.
LEVINE, JOSEPH, Statistical explanation of spontaneous freezing of water droplets, NACA Tech. Note 2234, Dec. 1950.
LUDLAM, F. H., The composition of coagulation elements in cumulonimbus, Q. J. R. Met. Soc., v. 76, pp. 52-58, 1950.
LUDLAM, F. H., Structure of shower clouds, Nature, v. 167, no. 4242, pp. 254-256, 1951.
MASON, B. J., The nature of ice-forming nuclei in the atmosphere, Q. J. R. Met. Soc., v. 76, no. 327, pp. 59-74, Jan. 1950.
REISS, H., Time lag in the nucleation of supercooled water clouds by silver iodide smokes, J. Chem. Phys., v. 18, pp. 529-533, April 1950.
WOODCOCK, A. H., Condensation nuclei and precipitation, J. Met., v. 7, pp. 161-162, 1950.
WOODCOCK, A. H., and M. M. GIFFORD, Sampling atmospheric sea-salt nuclei over the ocean, J. Marine Res., v. 8, no. 2, 1949.
WORKMAN, E. J., and S. E. REYNOLDS, Electrical phenomena occurring during the freezing of dilute aqueous solutions and their possible relationship to thunderstorm electricity, Phys. Rev., May 1, 1950.

Department of Meteorology (HRB),
University of Chicago,
Chicago, Illinois

(Communicated manuscript received May 31, 1951;
open for formal discussion until March 1, 1952.)

Transactions, American Geophysical Union Volume 32, Number 5 October 1951

REPORT OF THE COMMITTEE ON CLIMATOLOGY, 1950-1951

C. W. Thornthwaite, Chairman
Phil E. Church John R. Mather

In a survey of the present status of climatological instruction and research in this country, 112 letters were sent out to various colleges and government agencies. Replies have been received from 89. Of the 76 colleges interrogated, 64 have replied so far. Of these, 24 reported that they offered some graduate courses in climatology, but only two, Florida State University and the University of Washington, offered an advanced degree in climatology. Most of the other 24 offered the degree in geography or meteorology, with a major interest in climatology. Fourteen colleges offered no courses in climatology while 17 more indicated just one or two undergraduate courses in regional climatology or elements of climate. Twenty-eight colleges reported research in some phase of climatology. It consisted mainly of work performed by graduate students in the preparation of master's or doctor's theses. A more complete listing of the climatology courses taught in over 700 of the 800 colleges and universities in the United States will be found in the Directory of College Geography published by the University of Kentucky.

Summarized below are excerpts from the reports received from the schools and agencies which were most actively engaged in climatologic work.

Research in climatology in colleges

University of Arizona (Tree Ring Laboratory, E. Schulman)--During 1950 an ONR-sponsored project was begun with the objective of extending both the number of regions and the length of the records used to derive tree-ring histories of year-by-year river flow and winter rainfall for the Colorado River Basin. Extension to the upper Missouri and other river basins of the West, based on tree borings already obtained in good part, will follow during the next two years.

Clark University (Department of Geography, S. Van Valkenburg)--The past year we continued work on temperature deviations for the northern hemisphere (monthly sigma maps). . . We have also a number of Master of Science theses in climatology, such as a new Koeppen map of South America, a study of the climate of Alabama and Georgia using the technique of Russell as applied to Texas, and studies of yearly climatic variations in South Africa and India in order to determine critical areas.

Colorado A. and M. College (Division of Engineering, T. H. Evans)--We have recently constructed a wind tunnel with velocity up to about 80 mi/hr on an ONR contract on climatological factors such as evaporation, heat, and mass transfer from plane boundaries. We have proposals for further research in climatology involving both human and small animal objects.

Florida State University (Department of Meteorology, W. A. Baum)--The Department . . . is now engaged in research on fundamental problems in the broad field of theoretical climatology under contract with the Office of Naval Research. (This from ONR, M. A. Eaton) The purpose of this project is to obtain a theoretical representation of the annual variation in temperature at a geographical location in terms of components of the vertical heat balance for the atmosphere and Earth.

Harvard University (Blue Hill Meteorological Observatory, C. F. Brooks)--Our climatological work . . . consists of four phases: (1) maintaining a detailed record at a primary climatological station noted for its practically unchanging conditions of exposure or city influence over a period of 65 years; (2) making studies of the record, (a) both with respect to long-term trends in climate and (b) with respect to statistical combinations for statistical weather forecasting; (3) publishing climatological books and papers, of which the Conrad and Pollak "Methods in climatology" and the translation of Geiger's "The climate near the ground" were the most important in 1950; and (4) giving graduate instruction in climatology leading usually to the Ph. D. degree.

Iowa State College (Department of Agronomy, R. H. Shaw and G. L. Barger)--Research work is grouped under three classifications: (1) to record weather data in the immediate area of ex-

perimental field plots and to make available data . . . in a summarized form that can be better applied to the interpretation of agronomic data; (2) to study certain climatic and microclimatic effects on Iowa crops; (3) to determine specific conditions of climate pertinent to crop growth and agriculture in general, and to estimate the probability of occurrence of these conditions in terms of risk involved.

Johns Hopkins University (Laboratory of Climatology, C. W. Thornthwaite)--Climatic research is conducted at the Laboratory of Climatology under the joint sponsorship of the United States Air Force and the Seabrook Farms Company. The Laboratory is primarily concerned with problems of microclimatology and agricultural climatology. These involve the development and improvement of instruments for microclimatic observations and the detailed simultaneous and accurate observations of the properties of the air near the ground. In order to understand the heat and moisture balance at the Earth's surface, measurements of wind, humidity, and temperature gradients as well as of solar radiation are made. Instruments to measure air and dew-point temperatures, and evapotranspiration from a vegetation surface are being perfected and extensive work has been done on improving wind measurements. A multiple energy balance indicator to measure wind, radiation, and temperature simultaneously has been designed but it is not yet in operation.

Massachusetts Institute of Technology (Department of Meteorology, J. M. Austin)--Except for theses the major research related to a phase of climatology is W. Hewson's project on diffusion. This project is sponsored by the Geophysical Research Directorate of the Air Materiel Command.

McGill University (Department of Geography, F. K. Hare)--The Department has deliberately chosen as its specialization the study of the Arctic and sub-Arctic climates and their associated vegetation. . . Almost all the work being done comes under the category of climatological exploration, and consists in the investigation often in the field of aspects of the Canadian climate which remain so far little known. . . Investigations completed or in progress: (1) general investigation into the climatology of the Eastern Canadian Arctic and sub-Arctic . . .; (2) investigation into the climatological relations of the ice-cover of parts of the Eastern Canadian seas . . .; (3) investigation into the distribution of certain vegetation types within the boreal forest region of Eastern Canada, and the establishment of climatic correlations . . .; (4) detailed studies of certain special aspects of the Eastern Canadian climate.

Pennsylvania State College (Department of Earth Sciences, H. Neuberger)--Research that has been completed during the past year includes a Master of Science thesis entitled "Temperature distribution in the microclimatic layer" by A. V. Dodd. This work represents an analysis of data taken at the U. S. Regional Pasture Research Laboratory at State College in the layer up to 96 inches. Additional work is being done at this time by V. Sprague of the Pasture Laboratory and myself. Another master's thesis, "The variability of precipitation in the United States of America" by Y. Katz, is not merely a regional study but also contains a very nice treatment of methodological aspects. Some instrumental work on Landsberg's glass-rod method for UV integration has recently been published in the Transactions.

Rutgers University (Department of Meteorology, E. R. Biel)--As far as research projects are concerned, we are working on (1) climatic problems of New Jersey, (2) microclimatic practices in their broadest meaning (summarizing literature study), and (3) measurements in growing pasture plots.

University of Florida (Engineering and Industrial Experiment Station, R. A. Morgen)--If a broad interpretation be given to the term climatic research, the following projects may be considered as research associated with climatology and were either in progress or completed during the past year: (1) the effect of high-velocity wind and rain on building components; (2) prevention of tropical deterioration; (3) Florida rainfall patterns; (4) sferics; (5) radio-noise studies; (6) weather radar; (7) effects of atmospheric pollution on textiles; (8) solar-energy studies; (9) microseism studies.

University of Washington (Department of Meteorology and Climatology, P. E. Church)--Climatological projects under investigation: (1) heat budget in the upper 15 m of the ground; (2) frequency, magnitude, and duration of stable and unstable lapse rates in the bottom 50 m of air; (3) moisture gradient in the bottom 50 m of the air; (4) atmospheric pollution of Seattle.

Additional research being carried on in climatology

American Institute of Crop Ecology--Microclimatic latitudinal analogues: The purpose of this task is to organize into tabular, map, and descriptive form the microclimatic data for those parts

of Norway, Sweden, Finland, and Siberia which lie within the latitudinal range of Alaska and Canada, and to formulate the North American analogues for each station in the four countries. Completed - April 1950.

American Geographical Society--Juneau Ice Field Project: The purpose of this project is to make detailed glacier studies to obtain a better understanding of their physical characteristics and the climatic factors that influence their growth and decay.

Headquarters, Air Weather Service--The following examples of climatological development are grouped into various fields of development: (1) development of the use of indirect methods for derivation of data; (2) development of regional climatologies of statistical or mathematical functions; (3) development of techniques for presenting specific weather data for design problems; (4) development of regional specialization; (5) development of the derivation of probable data on recent weather from limited available data; (6) development of the use of special processing techniques; (7) development of the use of rapid transmission of climatic data for planning purposes; (8) development of data annotation methods.

Research and Development Board--There is a joint contract of the Army, Navy, and Air Force . . . with the National Research Council, Prevention of Deterioration Center, for investigations of the effect of climatic factors upon deterioration of materials. The Department of the Army, through the Office of the Quartermaster General, is engaged in preparing clothing zone maps based on temperature frequencies and clothing almanacs based on all climatic factors. Other research projects have been discussed in connection with the university concerned.

Department of the Army, Office of Quartermaster General--About half a dozen professional climatologists and a similar number of assistants are engaged in analyzing and describing climatic conditions, which affect military operations and logistics, in the Environmental Protection Section, Research and Development Branch, Office of the Quartermaster General. Their principal research activity is aimed at improving the methods of describing those aspects of climate which directly affect human activity and requirements, and at expressing climatic conditions, especially extremes, in terms of military risk.

Ontario Research Foundation--The following climatic research work is under way at the Foundation: (1) a study of the moisture balance in southern Ontario; (2) measurement of evapotranspiration at Toronto (and later at Guelph) and Norman Wells, N.W.T.; (3) a three-year experiment on controlled irrigation of red pine seedlings at the Ontario Forest Nursery; (4) a study of evaporation and runoff on a small basin near Toronto; and (5) a statistical study of the climate of northern Ontario.

U. S. Geological Survey--Research projects in climatology in the Water Resources Division include (1) the careful measurement of precipitation, soil moisture, ground-water storage, and runoff of a 17-sq.-mi. basin of homogeneous lithology near Salisbury, Maryland; (2) observation of climatologic and hydrologic phenomena to evaluate effects of changes in land use on stream flow; (3) study of the seasonal movement of soil moisture in relation to climate; (4) evaporation from Lake Hefner near Oklahoma City determined by three methods, (a) the water budget, (b) heat-energy budget, and (c) turbulent diffusion.

Building Research Advisory Board, Committee on Climatic Research--The Committee is studying the needs for data to enable architects and engineers to adapt buildings to wide climatic variations in the United States. According to the Committee's report to the Board on February 15, 1951, improved engineering would result in conservation of fuel and building materials, and reduced maintenance costs on both buildings and their contents. The report pointed out the absence of accurate data on United States climate, and the potential usefulness of a comprehensive climatic atlas in various programs related to defense as well as to construction.

Instruction in climatology

Florida State University (W. A. Baum)--The Department now offers the Master of Science degree in Meteorology and Climatology and it is anticipated that a doctoral program will be available within the near future. Formal courses in climatology now include the following: Fundamentals of climatology, three semester hours; Theoretical climatology, three semester hours; Microclimatology, three semester hours; Climate through the ages, three semester hours; Climatography, three semester hours.

Harvard University (Blue Hill Meteorological Observatory, C. F. Brooks)--Graduate instruction in climatology is available in the form of informal directed work in the Department of Geology and Geography and, in formal courses, at the Massachusetts Institute of Technology, by cooperative ar-

rangement. Candidates may work for master's or doctor's degrees with their major in climatology, but with substantial minors in other fields, such as statistics, geomorphology, and geography.

Iowa State College (R. H. Shaw and G. L. Barger)--Graduate work is offered for the degree of Master of Science in Agricultural Climatology. Students seeking the degree of Doctor of Philosophy may minor in Agricultural climatology or take a joint major in Agricultural climatology and some related field. The joint major is usually taken with some field of agronomy, botany, and statistics. On both degrees emphasis is placed on statistical training.

Johns Hopkins University (C. W. Thornthwaite)--The Johns Hopkins University offers only graduate training in climatology leading to the degree of Doctor of Philosophy through the facilities of its Laboratory of Climatology, Seabrook, New Jersey. Since the University does not offer the necessary prerequisite work in meteorology, students interested in climatology are expected to obtain their meteorology elsewhere. Formal courses offered in climatology include: Physical climatology, Statistical methods in climatology, Regional climatology, Microclimatology, and Physiological Climatology. Related courses include Hydrology, Oceanography, and seminars in Soils, and Problems of the tropics. In addition, a practical field course in microclimatology is offered year round. This is the most important part of the training, for it involves work on all of the many varied problems in microclimatology which arise at the Laboratory at Seabrook.

Massachusetts Institute of Technology (J. M. Austin)--The following instruction in climatology is offered at M.I.T.: General climatology, Regional climatology, Micrometeorological instrumentation, Micrometeorology, two courses in Applied climatology, Low-level turbulence and diffusion. B.S. and M.S. theses are possible in the fields of Applied climatology and turbulence. A twelve-weeks' graduate course in Climatology was offered at M.I.T. during the summer of 1950.

McGill University (F. K. Hare)--Climatological work is undertaken both in the undergraduate, general and honors degrees, and for the Master's and Doctor's degrees in the Graduate Faculty. Courses included: Climatology, Physical geography of the Arctic, Physiography, and Area studies.

New York University (B. Haurwitz)--As far as instruction is concerned, we are offering one undergraduate course and one graduate course in climatology, and, in addition, H. A. Panofsky is teaching a course entitled Theoretical climatology. There are also two courses in Statistical methods, one on the undergraduate and the other on the graduate level which may be considered as having a more direct bearing on climatology than the other topics in our curriculum.

Pennsylvania State College (H. Neuberger)--Our curriculum of meteorology includes a course in Physical climatology and Regional climatology. In addition, we offer further climatological work by means of an undergraduate seminar and a thesis. In our graduate curriculum we offer a course in Bioclimatology, Research in climatology leading to either a Master's or Doctor's degree. We also take up special topics of Microclimatology and Paleoclimatology in a lecture course entitled "Selected topics in advanced meteorology."

University of Illinois (J. L. Page)--In brief, we have the following offerings: Introductory meteorology (undergraduate), Agricultural climatology, Climates of continents (undergraduate), Analytical climatology (graduate), Bioclimatology, Research (thesis course), Advanced studies. Our offerings now make it possible for a person to take either an M.S. or Ph.D. with a major emphasis on Climatology.

Chanute Air Force Base, Illinois--A course in Climatology will be given for airmen at Chanute Air Force Base, Illinois, probably during the summer or early fall of 1951. The course will include subjects at both intermediate and advanced levels. The subjects to be given will include Synoptic climatology, Machine methods in climatology, Military uses of weather data, and Statistical climatology and its uses.

This is only a brief survey of the status of climatological work in this country. Several universities and agencies which might at present be conducting research or course work in climatology have not yet replied to our letters. The foregoing should serve, however, to indicate the trend of climatological work at present and to show what problems are being actively investigated.

Laboratory of Climatology (CWT and JRM),
The Johns Hopkins University,
Seabrook, New Jersey

(Communicated manuscript received June 1, 1951;
open for formal discussion until March 1, 1952.)

REPORT OF COMMITTEE ON THE CHEMISTRY OF NATURAL WATERS, 1950-1951

W. W. Hastings, Chairman

M. R. Huberty	S. K. Love	O. M. Smith
Russell M. Jeffords	Joseph Poland	H. A. Stoltenberg
Karl F. Keeler	Melvin Romanoff	Paul Weaver

In the list of members of the Committee given in the Directory [Trans., Oct. 1950], the name of O. M. Smith (1953) was not included because at the time of publication his acceptance had not been received.

The members of the Committee have diversified interests in the field of water chemistry. Poland is Chairman of the Research Committee on Ground Water of the AGU and his participation on the Committee on the Chemistry of Natural Waters should lead to close integration of the activities of the two Committees. Other members are either presently engaged in research studies or have active interests in such fields as geochemistry, treatment of natural water, chemistry of surface and ground waters, corrosion of metals underground, and conservation and development of water resources with special emphasis on their chemical content.

Inasmuch as the full membership of the Committee on the Chemistry of Natural Waters was not attained until recently, time has been too short to plan and complete any important projects. Furthermore, much attention of members has been given to activities in connection with the Defense effort and it has not been possible to compile a comprehensive statement of current research work on the chemistry of natural waters.

U. S. Geological Survey,
Washington 25, D. C.

(Communicated manuscript received April 27, 1951;
open for formal discussion until March 1, 1952.)

REPORT OF THE COMMITTEE ON GROUND WATER, 1949-1950

S. W. Lohman, Chairman

H. F. Blaney	R. M. Leggette	A. C. Swinnerton
M. L. Brashears, Jr.	G. W. Musgrave	H. E. Thomas
E. B. Burwell, Jr.	J. F. Poland	C. K. Wentworth

The present report concludes the duties of the above Committee, and the Chairman takes this opportunity to thank the members and others for their splendid cooperation during the triennium ended June 30, 1950.

Another in the series of reports on hydrology and physiography of limestone terranes, by A. C. Swinnerton, is given as an Appendix to this report.

The second Report of the Subcommittee on Ground Water of the General Committee on Research of the Society of Economic Geologists has been published [LOHMAN, 1950], but to date only one of the nine sponsored research papers--Geochemistry of ground water, by JOHN D. HEM [1950]--has been completed and published. It is hoped that papers on the remaining eight topics will be completed and published in Economic Geology without undue delay, as these reports should do much to stimulate further research in the several phases of the science of ground-water hydrology.

In 1949 ground-water studies were begun of the uranium-vanadium deposits in Mesa and Montrose Counties, Colorado, by the Mineral Deposits Branch of the Geological Survey on behalf

of the Atomic Energy Commission. These studies were undertaken to determine both present and past ground-water conditions in the ore-bearing rocks and the influence ground water may have had in the genesis and localization of the deposits. The studies are being made by David A. Phoenix under the supervision of Richard P. Fischer. S. W. Lohman has been assisting in an advisory capacity.

Roger Rhoades (U. S. Bureau of Reclamation, Denver, Colorado)--"Ogilivis Method" of measuring natural voltage created by the movement of fluids through capillary openings was tested for possible application to ground-water migration in attempts to localize zones of leakage at Wicklup Reservoir near Bend, Oregon, and to localize ground-water sinks believed to be present in the reservoir area of the proposed Benham Falls Reservoir site near Bend, Oregon. The results were inconclusive but supplied data for further tests and experiments.

Further studies of "pump-in" field permeability tests in sand suggest that their reliability varies directly with the uniformity of the grain size and degree of consolidation of the material. In silty and clayey material, the accuracy of the results appears to vary inversely with the amount of fines present. The major problem involved is the development of a satisfactory method of drilling test wells that will not change the nature of the materials too much by consolidation and segregation of fines.

H. G. Hershey (U. S. Geological Survey, Iowa City, Iowa)--A mobile electrical well-logging unit for measuring well temperatures, hole diameter, rate and direction of flow of water, conductance of water, electrical resistance of the rock formations, and the natural electrical potential was used to study many deep wells throughout Iowa. The equipment has been particularly useful in determining the relative quantities of water flowing into a well from each of the several aquifers that are penetrated and to indicate leaks in the cased parts of wells. The water in deeper aquifers in some parts of the State has been considered unpotable; however, these preliminary studies suggest that the deep water may be of reasonably good mineral character if shallow mineralized waters are excluded.

Detailed studies on well cuttings, subsurface stratigraphy and structure, and the stratigraphic occurrence of ground water throughout the State were continued as a requisite part of the investigation. Especial attention has been given to precise delineation of buried channels in the bedrock surface of eastern Iowa, and to the occurrence of water-bearing gravels along these channels.

Paul H. Jones (U. S. Geological Survey, Baton Rouge, Louisiana)--Preliminary results of resistivity tests of formation samples from sand aquifers show that the porosity and the electrical "cementation factor" of such aquifers can be determined by use of a resistivity cell and potentiometer.

The porosity of such samples, as determined volumetrically, ranged from 25 to 40 pct, but the cementation factors for sands of each geologic formation were relatively constant. For a given formation, therefore, an experimentally determined cementation factor can be established; and simple measurements of sample resistivity in the cell can be interpreted in terms of sample porosity.

This procedure has been applied in core analysis by oil companies [GUYOD, 1944], but prior to the present time it is believed drill cuttings of unconsolidated fresh-water sands have not been studied in this manner.

A technique for quantitative interpretation of the quality of water in sand aquifers from the electric logs of wells has been devised and widely applied by the staff of the Louisiana district during the last two years. Drill cuttings of sand are washed, thoroughly rinsed in a dilute salt solution of known resistivity, placed in a standard resistivity cell, and the resistivity of the saturated sand measured. The formation factor of the sand (the ratio of the resistivity of saturated sand to the resistivity of the water of saturation) is determined and applied, using the electric log, to calculate the resistivity of the water in the aquifer. After correction for temperature, the resistivity values are interpreted in terms of dissolved solids, using curves plotted upon the basis of scores of resistivity-dissolved solids values for samples of waters from wells tapping aquifers of the same geologic age in the region.

Finally, hypothetical chemical analyses are prepared for the water from each sand by plotting ion concentrations against the total dissolved solids for many water samples from wells tapping aquifers of the same geologic age in the region.

Results of field application of the method described above have been excellent, and the technique has, in addition, enabled preparation of regional maps showing the maximum depth of occurrence of fresh water, based upon the electric logs of many oil-test wells.

A paper entitled "Electric logging applied to ground-water exploration," by P. H. Jones and T. B. Buford, will be published in an early issue of Geophysics.

Robert R. Bennett (U. S. Geological Survey, Baltimore, Maryland)--Some time was spent in furthering the development of a geophysical well-exploration unit.

Several detailed pumping tests were run in the Eastern Shore of Maryland that gave valuable and significant information on the effect of variations in vertical permeability on ground-water flow.

A study was made of the relation of flow-net patterns to the areal changes in transmissibility of the principal water-bearing formations in the Baltimore area. The approximate coefficient of transmissibility in the different districts was determined from the density of flow paths and potential drops surrounding each district.

Wilbur T. Stuart (U. S. Geological Survey, Ishpeming, Michigan)--The study of the relation of ground water to mine drainage in the northern peninsula of Michigan has been extended to the Marquette iron range in the vicinity of Ishpeming and Negaunee. A map outlining the ground-water reservoirs in the vicinity of existing mines and a water-table map showing the contributing sources of recharge are being prepared. Gagings of the streams, creeks, and mine-water-waste ditches indicate that some recharge to ground-water reservoirs has taken place from these sources and, in places where land subsidence due to mining operations has broken the bedrock surface, considerable downward percolation of water is induced into the mine workings. Efforts to dewater the periphery of these subsidence areas by means of wells pumping from the overburden have not been too successful because, as the saturated thickness above the bedrock decreases, the yields of the wells also decrease. Elimination of the sources of recharge such as diversion and fluming of the surface streams, drainage of lakes, and combinations of the above with pumping of the underground reservoirs have in most cases resulted in decreased flows in the mine workings. Studies of the permeability of the rock formations are being made by laboratory methods to determine if other methods of development and mining can be devised that would result in better control of ground water in the mines.

G. H. Taylor and H. A. Waite (U. S. Geological Survey, Lincoln, Nebraska)--An hydrologic laboratory has been established by the U. S. Geological Survey at Lincoln, Nebraska, for determining the physical properties of water-bearing materials and for conducting research in this field.

H. C. Barksdale (U. S. Geological Survey, Trenton, New Jersey)--A study at Seabrook Farms under the supervision of C. W. Thornthwaite seeks to determine infiltration rates over fairly large areas by applying water irrigation sprinkler-type guns. Forested areas were found to have surprisingly high rates of infiltration compared to similar soil that had been under cultivation for many years.

Another project seeks to determine the effect upon infiltration and ground-water recharge of various types of forest management including periodic controlled burning in the winter as an aid in preventing forest fires and in establishing the desired types and varieties of trees. The forestry experiments are being conducted by the U. S. Forest Service. The hydrologic studies are sponsored by the New Jersey Cranberry Growers Association to determine what effect, if any, the burning might have on infiltration and runoff. Thus far the hydrologic studies have been limited to measurement of soil moisture and the interception of moisture by vegetation, but it is hoped to determine the effect of such practices upon the water table.

J. W. Lang (U. S. Geological Survey, San Antonio, Texas)--Potable water was discovered by test drilling in Miocene (?) sands between the depths of 2,200 and 2,600 ft in southeastern Houston as the result of cooperative studies of electric logs of borings for oil and gas by the Houston Water Department and the Geological Survey. Measurement of the artesian head indicates that the water would flow at the surface at a point about 35 ft above sea level. Flow tests indicate that the deep sands below a depth of 1,800 ft have a lower transmissibility and will yield considerably less water than those above that depth.

Withdrawal from aquifers between the depths of 450 and 1,800 ft has increased from 75 to 150 million gallons per day during the last decade and has lowered the artesian head 70 to 100 ft in the

Houston-Pasadena industrial area. It is significant that this heavy withdrawal has had no apparent effect on the head in the aquifers at a depth of 2,200 ft and more, and that the deep waters are fresh, as this minimizes the danger of salt-water contamination from the nearby Gulf of Mexico.

References

GUYOD, HUBERT, Electrical well logging, Oil Weekly, pt. 13, p. 81, Aug. 7 - Dec. 4, 1944.
HEM, JOHN D., Geochemistry of ground water, Econ. Geol., v. 45, no. 1, pp. 72-81, 1950.
LOHMAN, S. W., Report of the Subcommittee on Ground Water of the General Committee on Research of the Society of Economic Geologists, Econ. Geol., v. 45, no. 1, pp. 70-71, 1950.

U. S. Geological Survey,
Denver, Colorado

APPENDIX 1--HYDROLOGY AND PHYSIOGRAPHY OF LIMESTONE TERRANES

A. C. Swinnerton

New and increased activity has been apparent in the two years since the 1947-1948 report [Trans. Amer. Geophys. Union, v. 30, pp. 600-601, 1949] in the several aspects of the hydrology of limestones and their geomorphic expression. Much of the expansion of interest arises from the enlargement of the work of the U. S. Geological Survey. Increase in activity is also noticeable in regard to the problems of solution of limestone and of cavern development.

Studies by J Harlen Bretz and Leland Horberg of the University of Chicago in the vicinity of Carlsbad, New Mexico, have resulted in two papers relating to the origin of the caverns [BRETZ, 1949] and their relation to the geologic history of the region [HORBERG, 1949].

The West Virginia Geological Survey issued a report on the caverns of West Virginia [DAVIES, 1949] which includes descriptions of some 400 caves accompanied by many maps, photographs, and a considerable variety of data.

The National Speleological Society has actively increased its scientific interest in caverns as manifest in its last two bulletins (Bull. 10, 1948, and Bull. 11, 1949). The former is specifically devoted to the caves of Texas; the latter to a variety of articles including a list of some 52 foreign journals of speleology.

G. T. Warwick (University of Birmingham, England) indicates considerable geomorphic interest on the part of the cave research group in England. This organization publishes both a News Letter and Transactions.

Table 1--Yield of 100 New Jersey wells drilled in limestone related to diameter
(Range in yield, 0-815 gpm)

Size	Number	Average yield	Average specific capacity
inch		gpm	gpm/ft drawdown
6	67	18.5	1.7
8	20	216.5	37.0
10	8	201.5	112.4
12	5	384.0	10.3
all	100	40.8	18.2

Table 2--Yield of 100 New Jersey wells drilled in limestone related to depth
(Range in yield, 0-815 gpm)

Depth	Number	Average yield	Average specific capacity
ft		gpm	gpm/ft drawdown
50-150	51	46.7	20.1
150-250	35	88.1	9.3
250+	14	260	33.2

N. Llopis Lladó (University of Oviedo, Spain) is director of a new journal published at the University of Oviedo entitled Speleón, devoted to hydrology, karst phenomena, and speleology.

Kirk Bryan (Harvard University, Cambridge, Massachusetts) supplied information that John P. Miller is investigating the solubility of calcite in water and carbon dioxide at ordinary temperatures and pressures. This chemical investigation is being made to lay the foundations of sound chemistry for the consideration of limestone problems and will constitute Miller's doctoral thesis.

Robert M. Garrels (Northwestern University, Evanston, Illinois) is also studying the nature of calcite solubility, particularly with reference to the pH effect.

Tables 1 and 2, prepared by Henry Herpers and reported by Meredith E. Johnson (New Jersey Geologic and Topographic Survey), relate to wells drilled in limestones in New Jersey.

E. J. Schaefer (U. S. Geological Survey, Columbus, Ohio)--Pumping tests have been performed on limestone formations at Yellow Springs, Columbus Grove, Bluffton, North Baltimore, and Toledo. Transmissibilities have ranged from about 6,000 to 20,000 Meinzer units; coefficients of storage have been in the magnitude of about 2×10^{-4}. However, in each test hydraulic boundaries were noted that were closer to the wells tested than the known geologic limits of the formation. Since these boundaries represent areas of practically zero transmissibility the tests indicate that changes from relatively high to practically zero transmissibility are not uncommon. The work emphasizes that pumping-test data are needed to supplement geologic studies in planning of groundwater developments in limestone areas.

Preston McGrain (Indiana Flood Control and Water Resources Commission, Indianapolis, Indiana)--Recent papers by BRUNE [1949], MALOTT [1949], McGRAIN [1948, 1949], and WICKWIRE [1948] touch on the hydrology and physiography of limestone areas in Indiana.

Karst features have been recognized not only in the highly cavernous Middle Mississippian limestone but also in Devonian and Silurian limestones of Indiana. Consequently, a thorough investigation of proposed sites for dams and reservoirs in limestone areas is imperative. Associated with these investigations in unglaciated parts of Indiana is the study of the character and thickness of the residual clay that is found in close association with weathered limestone. Also, the position of the water table with respect to the ground surface in limestone terranes seems to have a direct bearing on the development of karst features and is noted wherever possible.

In addition to the papers cited above, Clyde A. Malott completed a paper on the swallow holes of the Lost River region for publication by the Indiana Academy of Science. William J. Wayne described a karst valley near Bloomington, Indiana, also for publication by the Indiana Academy of Science. W. D. Thornbury is studying the preglacial bedrock surface (which is dominantly Silurian limestone) along with his studies of the glacial geology in the upper Wabash Valley.

M. I. Rorabaugh (U. S. Geological Survey, Louisville, Kentucky)--Ground water in the middle Mississippian limestones near Hopkinsville, Kentucky, is now under study by the Geological Survey in cooperation with the Kentucky Agricultural and Industrial Research Board. Adequate supplies of water exist to depths of about 200 ft, below which the water is apt to be highly mineralized. Water is produced from a cavernous zone in the limestone immediately below the residual soil, and from joints at greater depth. Underground circulation is so free that pollution is widespread.

Two types of sinks have been recognized and will be mapped on aerial photographs. The majority of the sinks are broad and shallow and are assumed to be maturely developed inasmuch as they rarely show evidence of recent collapse. The small and steep-sided sinks now appearing and enlarging suggest a reinvigoration of subsurface erosion probably related to the entrenchment of the local streams.

At Louisville the Geological Survey, in cooperation with the City of Louisville and Jefferson County, is investigating the water-bearing properties of the Silurian and Devonian limestones underlying the glacial-outwash deposits of the Ohio River Valley. Wells produce large amounts of water from crevices apparently controlled by solution along joints and bedding planes. The requirements are additional industrial water and the disposal of used (warm) water through wells.

R. L. Cushman (U. S. Geological Survey, Tucson, Arizona)--A geologic investigation of a 150-sq-mi area of the Colorado Plateau in northern Arizona was made to determine if a dependable yield of 500 gpm could be obtained from wells or springs to supply a military installation. The work was done in the summer of 1949 in cooperation with the U. S. Army Engineers.

The Kaibab formation (Permian), a formation 300 to 400 ft in thickness consisting predominantly of limestone, was found to underlie the area at a depth generally less than 100 ft. The limestone is severely jointed and in some localities is cut by faults having displacements ranging from a few feet to more than 500 ft. Only one of 50 springs examined in the area issues from the limestone. This was a small seep, probably intermittent, emerging from a fault of about 10-ft displacement in the Beta member of the Kaibab formation. Since no wells in the area produce water from the Kaibab formation, it apparently does not store water, but acts as an avenue through which water is transmitted to the underlying formation. Elsewhere outside the area of investigation the Kaibab formation may be an aquifer. The regional water table lies about 700 ft below the land surface or more than 300 ft below the Gamma member of the Kaibab formation.

References

BRETZ, J HARLEN, Carlsbad Caverns and other Caves of the Guadalupe Block, New Mexico, J. Geol., v. 57, pp. 457-463, 1949.

BRUNE, GUNNAR M., Reservoir sedimentation in limestone sink-terrain, Agri. Eng., v. 30, no. 2, pp. 73-77, 1949.

DAVIES, W. E., Caverns of West Virginia, West Virginia Geol. Surv., v. 19, 1949.

HORBERG, LELAND, Geomorphic history of the Carlsbad Caverns area, New Mexico, J. Geol., v. 57, pp. 464-476, 1949.

McGRAIN, PRESTON, An example of lapies in the Indiana karst region, Ind. Acad. Sci., Proc., v. 57, pp. 148-152, 1948.

McGRAIN, PRESTON, Geological features of the proposed Cagle's Mill flood control reservoir, Ind. Acad. Sci., Proc., v. 58, pp. 163-172, 1949.

MALOTT, CLYDE A., Huddleson Cavern, a storm-water route of underground Lost River, Orange County, Indiana, Ind. Acad. Sci., Proc., v. 58, pp. 263-273, 1949.

WICKWIRE, GRANT T., Accelerated erosion due to industrial waste, Ind. Acad. Sci., Proc., v. 57, pp. 163-168, 1948.

Antioch College,
Yellow Springs, Ohio

(Communicated manuscript received April 16, 1951;
open for formal discussion until March 1, 1952.)

Transactions, American Geophysical Union Volume 32, Number 5 October 1951

DISCUSSION OF

"THE BEHAVIOR OF WATER DROPS AT TERMINAL VELOCITY IN AIR" by DUNCAN C. BLANCHARD

[Trans., v. 31, pp. 836-842, 1950]

James E. McDonald (Department of Physics, Iowa State College, Ames, Iowa)--The work reported by Blanchard in this paper must be regarded as an important effort in the experimental study of the stability of large raindrops. Stroboscopic photography has been admirably adapted by Blanchard to the task of revealing rapid changes in drop shape as well as showing details of drop breakup. Since publication of Blanchard's work provides virtually the sole source of observational information relative to raindrop dynamics, the writer would like to ask several questions in an effort to elucidate several points that arose in his mind in studying the paper.

(1) Has a turbulence survey of the working jet been made with any low-lag anemometer of small dimensions (for example, hot-wire)? In judging the applicability of the experimental results to the corresponding meteorological problems, it is indispensable to know the extent to which drop deformation, and still more, drop breakup, may be induced by fine-grained turbulence in the jet. Blanchard states that the natural frequencies of oscillation of the drops are in excess of about 25/sec, so one must ask whether turbulence in the frequency range of about 10 to 100 per second is or is not appreciable in the working jet. Possible blower pulsations, breakup of larger eddies into smaller eddies by the screen mesh, and absence of a contraction cone just upstream of the working jet are all factors rendering this possible.

It must be pointed out that this information concerning turbulent frequencies in the tunnel is necessary, but unfortunately not sufficient information for judging the carryover of Blanchard's observations to actual cloud physical problems. One must also know what turbulent frequencies may be present in the clouds themselves to influence drop dynamics. Blanchard implies at one place in his paper that there is within clouds appreciable turbulence of the sort conducive to drop breakup; but this view needs to be accepted with caution. The notorious "turbulence" of cumulonimbus clouds is that detected not by a small low-lag anemometer, but by large aircraft whose dimensions and horizontal speeds are such that changes of only a few per cent in the vertical velocity of the air over horizontal distances of several tens of meters register as "marked turbulence," whereas such large-scale heterogeneity of the velocity field could have practically no influence on drop breakup. Since it would seem possible some day to determine the fine-grained turbulence spectrum of clouds, thus filling in one-half of this picture, it is recommended that the other half be supplied by the inclusion of quantitative information as to wind-tunnel turbulence in reports on experimental studies of drop breakup.

(2) To what extent is the unnatural mode of formation of drops (extrusion from a horizontally held medicine dropper into the jet) responsible for the absence of drop symmetry about the vertical axis? If Figure 2 of Blanchard's paper is representative of the usual injection technique, then the extrusion process must be suspected of being chiefly responsible for this eccentricity, for it imposes both hydrodynamic and aerodynamic asymmetry upon the drop at the moment of its entrance into the jet. If the photographs on which Figure 5 was based were taken within only seconds after the instant of extrusion, surface and viscous forces might not have had time to bring the drop into the expected shape of a revolute. Thus one is led to the corollary question: How long a period elapsed, on the average, between extrusion and photographing? This question becomes of crucial importance when one assesses the meteorological applicability of the breakup photographs. The reportedly typical evolution of a narrow neck between two bulbous extremities just prior to all of the breakups Blanchard observed is at least indicative of a preferred axis of horizontal elongation of the sort that could easily be imposed upon the drop by the extrusion process. It seems essential to know whether this may have been the case before applying Blanchard's results to the corresponding meteorological problem.

The writer was fascinated by the many subtle dynamical implications of Figure 4, but he finds difficulty in accepting it as evidence of "the extreme sensitivity of large drops to turbulence."

The perturbation employed seems anything but delicate, especially in view of what must have been marked transverse eddying motion in the ascending gust front induced by using so non-streamlined a shutter as the hand. Is it likely that raindrops in a natural cloud ever experience velocity discontinuities as abrupt as that employed experimentally here?

In addition to raising the above questions, the writer would like to make several suggestions in the hope that some of them may contribute to future studies of these interesting and meteorologically important problems.

(1) Some technique for the axially symmetric extrusion of drops seems highly desirable. A narrow glass tube bent into a right angle with its horizontal leg entering the jet just above the screen and with its vertical stem extending up along the central axis of the jet might satisfy this requirement fairly well. The decided advantage of such a device would be its complete freedom from hydrodynamic axial asymmetry and its steadiness (which would eliminate impulsive angular motions possibly responsible for the drop rotations reported by Blanchard).

(2) If a turbulence survey of the jet should reveal that resonant breakup may be occurring, use of an entrance cone of large contraction ratio (as much as 100:1) is recommended as a means of suppressing turbulence [POPE, 1947].

(3) Published photographs of drop behavior would be rendered more generally useful, especially in theoretical studies, if the updraft velocities were stated for each case and if a fairly accurate length scale could be presented. Knowing the equivalent spherical diameter is helpful, but the highly deformed drops preclude translation of this figure into anything more than a very crude length scale.

(4) A series of photographs of stable drops in the entire range from the upper limit of stability down to drops so small that no asphericity is apparent could be made and would constitute a valuable addition to the literature.

(5) Above all, further wind tunnel work on coalescence and "bounce-off" is greatly needed for the quantitative analysis of precipitation theories [HOUGHTON, 1950]. Almost every modern theory of precipitation invokes coalescence at one stage or another to account for at least a part of the growth of large raindrops, yet the experimental evidence for its effectiveness is almost non-existent.

Finally, it seems in order to ask if an incorrect implication may not have been made by the statement, "Far from being tear-shaped [EDGERTON and KILLIAN, 1939; LENARD, 1904; SPILHAUS, 1948] the drop is relatively flat . . ." None of the investigators referred to in this statement suffered the misconception, so strongly ingrained in the layman's mind, that large falling drops exhibit the form conventionally described as tear-shaped.

References

HOUGHTON, H. G., A preliminary quantitative analysis of precipitation mechamisms, J. Met., v. 7, pp. 363-369, 1950.
POPE, A., Wind-tunnel testing, pp. 60-62, Wiley, 1947.

Duncan C. Blanchard (Division of Meteorology, Pennsylvania State College, State College, Pa., now at Woods Hole Oceanographic Institution, Woods Hole, Mass., Author's closure--McDonald has brought out several points which are indeed vital to the study of raindrop dynamics. The carryover of laboratory results to the actual case must be carefully considered.

Turbulence within the air stream will influence drop oscillations. A series of measurements taken across the air stream with a small pitot, whose pressure variations were indicated by an inclined draft gage, showed that no large-scale turbulence existed. However, as McDonald states, such a high lag anemometer would not indicate fine-grained turbulence arising from blower pulsations or screen eddies. Unfortunately, micro-measurements were not made. I wholeheartedly agree with McDonald that any future work should be done with thorough analysis of the extraneous conditions.

Concerning the question of turbulence within cumulonimbus clouds the writer must agree with McDonald that our knowledge of the small-scale turbulence is very slight. Also, admittedly, the use of the hand in causing turbulence is anything but a delicate procedure. Drop disintegrations, however, have been brought about by much less violent turbulence. If the rectangular control de-

vice (item 1, Fig. 1 of the paper) is removed, the drops will slowly be carried upward. At a height of about two meters above the top of the tunnel a majority of the large drops undergo breakup. There, the turbulence is apparently not pronounced, because about 90 pct of the drops broke up not by violent disintegration but by splitting into two parts with perhaps two or three small droplets evolving from the narrow neck of water which exists between the two parts just prior to the separations (see Fig. 3c of the paper).

The method of injecting the water drops into the air stream, as shown in Figure 2 of the paper, is misleading. The water was not injected from the medicine dropper in the position shown. The actual injection was done by holding the dropper vertically from above, with the open end down, along the central axis of the air stream. The water was slowly extruded at the point where it would remain suspended. As the water emerged from the dropper it flowed symmetrically outward to form the usual oblate spheroid. No water was blown upward around the stem of the dropper. Removal of the dropper was accomplished by lifting it vertically out of the air stream. No visible effect of hydrodynamic or aerodynamic asymmetry was observed on the drop. The injection of drops from a horizontally held medicine dropper is actually very difficult to achieve.

In answer to McDonald's comments concerning the references pertaining to tear-shaped drops, the writer was quite aware that the investigators cited realized that a large water drop at terminal velocity is not tear-shaped. Their work was cited merely for the benefit of any readers who may want to study further the work of others who, either in writing or pictorially, touched on the subject of the shape of water drops at terminal velocity. The references should have been placed at the end of the respective sentence rather than after "tear-shaped."

McDonald's suggestions for further work in this field are well worthwhile. Stroboscopic photography might well serve to give us a better insight into the manner in which drops coalesce and "bounce-off" upon collision.

DISCUSSION OF

"FORCES EXERTED BY WAVES ON A SLOPING BOARD"
by W. S. HAMILTON

[Trans., v. 31, pp. 849-855, 1950]

John H. Carr (California Institute of Technology, Pasadena, California)--Although the author of this paper makes it clear that a sloping board of moderate proportions can only be an effective breakwater for waves of very short length, the writer has been approached by persons who conceive such a breakwater to be of universal application. The purpose of this discussion is therefore to elaborate on the author's remarks as to the effectiveness of a sloping board as a breakwater, and in particular to point out the importance of the ratio of wave length to water depth in analyzing the behavior of a surface obstacle such as a sloping board.

In order to illustrate this point, a series of experiments was made at the Hydraulic Structures Laboratory of the California Institute of Technology, in which the configuration of the sloping board was that of Figure 5 of the paper, with $\sin\theta = 0.15$. In these experiments, the ratio of wave length to board width, ℓ/B, had a constant value of four, while the wave length to water depth ratio was varied over a range from two to eight. These experiments were made in a channel 120 ft long by 4 ft wide, with a water depth of one foot. The channel is equipped with a wave machine at one end and an efficient absorbing beach at the other. Transmitted wave height was measured by four electrical conductivity wave-height measuring elements positioned 4, 8, 12, and 16 ft behind the board, and the incident and reflected wave heights were determined by direct measurement of the maximum and minimum amplitudes of vertical water motion in the region to seaward of the board by means of a linear array of eight elements spaced four inches apart. This technique is based on the separation of an incident and reflected wave system of unequal amplitudes i and r into a progressive wave of amplitude (i - r) and a standing wave of amplitude (2r). Thus, points corresponding to nodes of the standing wave component have vertical water motion amplitudes of (i - r), and points corresponding to antinodes have amplitude (i + r). The surveying technique, which is carried out over at least one wave length with closely spaced measuring points, therefore provided a direct measurement of (i + r) and (i - r), from which i and r are readily determined. The direct measurement of incident, reflected, and transmitted wave heights permits the calculation of a coefficient of dissipation, which is analogous to the reflection and transmission coefficients r/i and t/i, in that it is the square root of the ratio of energy dissipated by the barrier to that incident at the barrier.

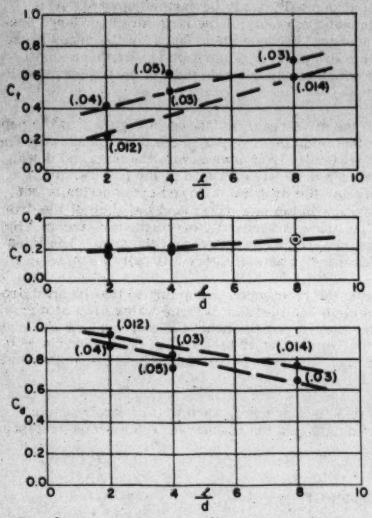


Fig. 9--Transmission, reflection, and dissipation of waves by a sloping board of constant $\ell/B = 4$; wave steepness shown by numbers in parentheses

$$C_d = \sqrt{Ed/Ei} = \sqrt{1 - [(r/1)^2 + (t/1)^2]}$$

An unfortunate omission of the paper is that the water depth used in the experiments is not stated; however, inspection of Figure 3 suggests that the water depth was two feet. The starting point of our experiments was therefore a half-scale model of the case for $\ell/B = 4$ of the original, with $\ell = 2$ ft, B = 0.5 ft, and d = 1 ft. Variation of ℓ/d with constant ℓ/B was obtained by varying both ℓ and B with constant d, with values of $\ell = 4$ ft, B = 1 ft, and $\ell = 8$ ft, B = 2 ft. Two values of wave steepness (H/ℓ) were used for each value of ℓ/d, to indicate the effect of this parameter. The results of these experiments are shown in Figure 9, in which C_t, C_r, and C_d are plotted as functions of ℓ/d.

The overall performance of this inclined plane as a breakwater is indicated by the plot of C_t. It is seen that as ℓ/d values characteristic of normal wind waves in harbor water depths are reached, the plane gives very little protection. What little protection that is afforded is further reduced with increasing initial wave steepness.

The plots of C_r and C_d permit some deductions concerning the effect of the board on the wave motion and so provide an understanding of the overall performance. The coefficient of reflection is substantially constant and is small compared to the coefficient of dissipation. This indicates that a board of such flat slope does not in itself reflect an appreciable amount of energy, since the vertical projected depth of the boards used varied in the ratio of 4:1, and if the board itself were the reflecting agency, the effect of this difference in size would be observed in the measurements of reflected wave height. A mechanism of wave reflection which is fairly insensitive to ℓ/d, and which is directly proportional to ℓ/B, is the mass of water trapped beneath the board which cannot experience vertical motion. (This phenomenon has been the subject of recent work at the Hydraulic Structures Laboratory, and a paper on this subject is now in preparation.) The constant value of C_r is therefore in accordance with the constant value of ℓ/B. It may be remarked that C_r will not become appreciable, say 0.6 or greater, for values of ℓ/B greater than two.

The reduction in effectiveness of a sloping board as an energy dissipator for increasing ℓ/d is a logical consequence of the well-known dependence of water particle velocity distribution on the ratio of wave length to water depth. For deep-water waves, $\ell/d < 2$, the kinetic energy of the wave motion is concentrated near the surface, and a sloping board of small submergence can "scoop up" and dissipate in turbulence a large part of the total wave energy. For shallow-water waves, $\ell/d > 10$, the energy is distributed nearly uniformly from surface to bottom, and the energy in the surface strata affected by the board is a lesser part of the total. In the present series of experiments, C_d exhibits such a decrease even though the ratio of affected strata to total depth was increased fourfold in the course of changing ℓ/d with constant ℓ/B and d.

The preceding discussion amplifies the author's remarks on the field of application of a sloping platform as a breakwater by explaining the mechanism of operation of such a device and so providing a basis for estimating its effectiveness for any assumed wave condition. In particular, it may be stated that, since waves of such a moderate period as eight seconds will have an ℓ/d ratio of nearly eight in a water depth of 30 ft, the experiments herein reported show that a sloping board of $\ell/B = 4$ (which is now a rather large structure with B/d = 2) will provide very little protection for this typical condition. The preceding analysis of the behavior of such structures also illustrates the necessity of stressing the water particle motion aspect of wave motion in problems of this sort where momentum changes are distributed non-uniformly from surface to bottom.

W. S. Hamilton (Northwestern University, Evanston, Illinois, Author's closure)--Carr is to be thanked for his interest in the writer's paper and for furnishing supplementary data. As he has estimated, the water depth for the original tests was about 2.3 ft. Thus in Figure 5 for $\ell/B = 4$ the value of ℓ/d would be 3.5. Carr's value of C_t for this one case in which the experiments are comparable agrees reasonably well with Figure 5.

It is apparent that any change in geometry (such as a decrease in depth or an increase in wave length) which increases the percentage of energy passing under the board will reduce its effectiveness as a breakwater. Figures 4, 5, and 6 show the effect of varying ℓ/B and ℓ/d simultaneously. Carr has found the effect of changing ℓ/d for a single value of ℓ/B. Complete data on the subject would include both ratios as independent variables. Moreover, because decreasing the depth and increasing the wave length have parallel effects on the energy distribution, there is the possibility of combining the two ratios into a single parameter (such as ℓ^2/Bd) against which C_t would plot with reasonable consistency.

DISCUSSION OF

"NUMERICAL SOLUTIONS FOR TILE DRAINAGE OF LAYERED SOILS"
by JAMES N. LUTHIN and R. E. GASKELL

[Trans., v. 31, pp. 595-602, 1950]

Abdel-Aziz I. Kashef (School of Civil Engineering and Engineering Mechanics, Purdue University, Lafayette, Indiana)--Numerical methods have proven to be very powerful tools in various practical fields. The authors' paper is a very interesting addition to the available knowledge of underground seepage problems. Problems with complex boundaries that defied mathematical treatment can now be solved easily, numerically. SHAW and SOUTHWELL [1941] solved dam problems with free water surfaces as their upper boundaries by the relaxation method. By the same method, YANG [1949] solved the water table (or unconfined) well problem in the steady state, and VAN DEEMTER [1949] solved the tile drainage problem. The relaxation method, which was originated by Southwell, is a numerical one, yet its techniques are entirely different from the method presented by the authors. The authors' solution is obtained by the iterative method discussed in detail by FROCHT [1948]. Equation (2) in their paper is credited to LIEBMANN [1918] and known after his name. By the relaxation method, (2) changes to

$$\phi_A + \phi_b + \phi_c + \phi_H - 4\phi_a = R \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

where R is a residual that should be liquidated by the relaxation technique. Block relaxation is an example of one of these techniques and its equivalent by the iterative procedure is known as "block iteration" [FROCHT, 1948]. It is the intention of the writer to emphasize the fact that although the iteration and relaxation methods have the same basic ideas, they widely vary in their techniques. The method presented by the authors should properly be described as a method of iteration.

References

FROCHT, M. M., Photoelasticity, v. 2, Chap. 8, pp. 238-296, John Wiley, 1948.
LIEBMANN, H., Sitzber. der math.-phys., Klasse, Bayer. Akad., München, p. 385, 1918.
SHAW, F. F., and R. V. SOUTHWELL, Problems relating to the percolation of fluids through porous materials, R. Soc. Proc. (London), v. A178, pp. 1-17, 1941.
VAN DEEMTER, J. J., Results of mathematical approach to some flow problems connected with drainage and irrigation, Applied Scientific Res., The Netherlands, v. A2, no. 1, pp. 33-53, 1949.
YANG, S., Seepage toward a well analyzed by the relaxation method, doctoral thesis, Harvard University, 1949.

James N. Luthin and R. E. Gaskell (Authors' closure)--We sincerely appreciate the remarks of Kashef, and agree with him that numerical procedures, applied to previously unsolvable problems, look very promising. We are especially happy since that was, implicitly at least, the principal thesis of our paper.

We did not foresee objections to calling the procedure used, the relaxation method. The relaxation method and iteration method are basically the same because relaxation is a special case of iteration--Newton's method for solving equations and Picard's method for solving differential equations are other special cases. All these methods are means of improving an estimated or previously calculated approximate solution.

Southwell applied the descriptive term "relaxation" because in his earlier papers he had constraints to be relaxed. An already existing iteration procedure [von MISES and POLLACZCK-GEIRINGER, 1929] used the same notion; but, in that method, ignoring an equation corresponds to imposing a constraint. If all but one equation is ignored, the constraints are relaxed one at a time, but if more than one is left to be considered, we have "block relaxation." The name "relaxation" is in order if constraints are relaxed or equations are ignored. It makes no difference whether there is a residual or not. In fact, a residual is used in Newton's method, and aids in choosing the next approximation--the same purpose it serves in the relaxation method.

We believe, therefore, that Southwell's term "relaxation" appropriately describes the method used in the paper. The key to the method is the phrase (p. 596) "the value of the head at each point being replaced by the average of its four neighbors," which means, of course, that all other equations involving the head at these and other points are ignored.

Reference

von MISES, R., and H. POLLACZCK-GEIRINGER, Praktische Verfahren der Gleichungsauflösung, Zs. für Angewandte Mathematik und Mechanik, v. 9, pp. 58-77, and 152-164, 1929.

DISCUSSION OF

"RAINFALL, INFILTRATION, AND HYDRAULICS OF FLOW IN RUNOFF COMPUTATION"
by H. N. HOLTAN and M. H. KIRKPATRICK, JR.

[Trans., v. 31, pp. 771-779, 1950]

Leonard Schiff (Soil Conservation Service, Research, Bakersfield, California)--It would seem desirable to associate infiltration curves with soil-moisture contents and land use as occurs in nature, such as the writer has illustrated [SCHIFF, 1951a]. The point at which the infiltration curve intersects the intensity graph must be determined in order to obtain excess rainfall or the supply to surface runoff [SCHIFF, 1951b]. Increments of excess rainfall may be converted into the depth of detention storage and rate of surface runoff. For any time interval T_1 to T_2, when the rainfall rate exceeds the infiltration rate, excess rainfall, E, is

$$E = (i - f_{av})(T_2 - T_1)/60 = (Q_{sc-2} - Q_{sc-1}) + (D_{s-2} - D_{s-1}) \quad \ldots\ldots\ldots (1)$$

where subscripts 1 and 2 represent the values of the symbols used at the beginning and end of the time interval, T_1 to T_2, respectively, i is the rate or intensity of rainfall, f_{av} is the average infiltration rate for the time interval (the prismoidal formula may be used if greater accuracy is needed), Q_{sc} is the quantity of surface runoff, and D_s is the depth of detention storage. For most cases, equation (1) may be written

$$E = i - [(f_1 + f_2)/2](T_2 - T_1)/60 = [(q_{sc-1} + q_{sc-2})/2](T_2 - T_1)/60 + (D_{s-2} - D_{s-1}) \ldots (2)$$

where f is equal to the infiltration rate and q_{sc} is equal to the rate of surface runoff; other symbols are the same as given in (1).

The equation used by Holtan and Kirkpatrick seems limited to the case where the rate of surface runoff and detention storage are zero at the beginning of a computed amount of excess rainfall. Actually, the excess rainfall produced by a rate of rainfall in excess of the infiltration rate may more likely occur when detention storage and rate of surface runoff are specific amounts depending upon the storm pattern and infiltration curve. The bookkeeping equation, from (2), used by the writer [SCHIFF, 1951b] for the development of the hydrograph is

$$E = [(q_{sc-1} + q_{sc-2})/2](T_2 - T_1)/60 + (D_{s-2} - D_{s-1}) \quad \ldots\ldots\ldots\ldots (3)$$

Starting at the beginning of excess rainfall, as computed in (1), it is a simple matter to balance this "excess - detention - rate" bookkeeping equation for a given or anticipated storm. The time period, $T_2 - T_1$, selected is the approximate time of concentration of the watershed in question; this time may vary somewhat with little effect on the results. The time of concentration selected is the time associated with the higher rates of surface runoff. If sufficient data exist for the determination of detention storage - rate of surface runoff relationships, the time of concentration for a watershed may also be approximated and used in establishing hydraulics of flow. Methods of estimating the time of concentration are well established in the literature.

At the beginning of excess rainfall q_{sc-1} and D_{s-1} are equal to zero. To balance (3), q_{sc-2} is assumed and the related D_{s-2} selected. The detention storage - rate of surface runoff relationships reflect the effect of the physical characteristics of a watershed on the excess rain fall. Methods of determining such relationships have been established by various other investigators and the writer [SCHIFF, 1951c]. These relationships plot nearly as straight lines on logarithmic paper and are different on rising and falling stages. To determine such relationships for a given watershed would require data for a storm on such a watershed producing fairly high rates of surface runoff. It would also be possible to estimate such relationships from a reasonably similar watershed from which hydrologic data were available. The bookkeeping equation is balanced for each successive time interval in the storm. The rates of surface runoff for all time intervals are thus determined and when plotted establish the hydrograph.

The equation and approach by Holtan and Kirkpatrick seem to cover somewhat of a special case, which, however, may give reasonable peak rates for certain problems. At least the relative effect of size of watershed and detention storage - rate of surface runoff relationships are reflected. The equation and approach given in this discussion are believed to cover the hydrology of a watershed from a fundamental point of view. The bookkeeping equation permits the development of the hydrograph from which total runoff may be obtained as well as the peak rate. Also, this approach may show the effect of land use on the hydrograph.

References

SCHIFF, LEONARD, Hydrology of surface supplies to runoff, Soil Conservation Service Tech. Pub. 90, 1951a.

SCHIFF, LEONARD, Hydrology of rates and amounts of surface runoff from single and mixed cover watersheds, 1951b.

SCHIFF, LEONARD, Surface detention, rate of runoff, land use, and erosion relationships on small watersheds, Trans. Amer. Geophys. Union, v. 32, pp. 57-65, 1951c.

H. N. Holtan and M. H. Kirkpatrick, Jr. (Authors' closure)--Runoff from an observed or assumed rainstorm can be quite accurately determined by application of data on infiltration, depression storage, and hydraulics of flow. Figure 12 is a graph showing the application of infiltra-

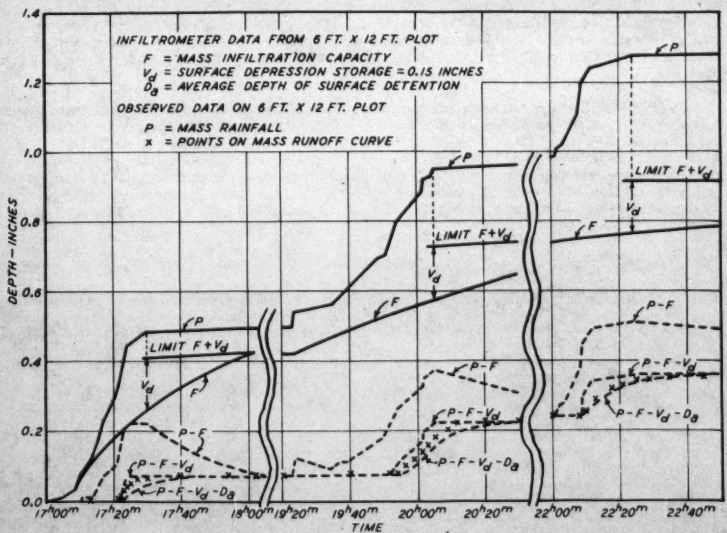


Fig. 12--Application of infiltrometer data to rainstorm of October 22, 1941 on plot 63, Edwardsville, Illinois, to illustrate the function of surface depression storage in computing runoff

tion data to the rainstorm of October 22, 1941 on Plot 63 at Edwardsville, Illinois, to illustrate the function of surface depression storage in computing runoff. In this illustration, infiltration pertains beyond each cessation of rainfall to the extent of surface depressional storage. The 0.15-inch depression storage is not a very impressive quantity in itself but considering that it is depleted and replenished three times during this rain it becomes a considerable quantity in computing the entire runoff curve. If depression storage were non-existent, the P - F curve of Figure 12 would have paralleled rainfall during intensity inadequacies and 0.45 inch more of rainfall would have been available to runoff. The P - F curve (without recessions) would have been considered as rainfall excess rather than the curve labeled P - F - V_d. In Figure 12, the curve P - F - V_d was proportioned to runoff and related detention by use of a formula later condensed to

$$E - Q_1 = (q_1 + q_2)T/120 + D_2$$

where

E = Rainfall in excess of infiltration and surface depression storage (P - F - V_d)
Q_1 = Total mass runoff in inches at beginning of time increment
q_1 = Rate of runoff in in./hr at beginning of time increment
q_2 = Rate of runoff at end of time increment
T = Time increment in minutes, usually chosen as three to five minutes
D_2 = Surface detention, in inches, needed to produce q_2

A very significant difference in results would be obtained if depression storage were not considered. Since the error is cumulative with each rainfall inadequacy, estimates of total runoff would be greatly affected.

Estimates of peak rate of runoff would be less affected by depression storage as is indicated by the similarity of slopes for rises of the P - F and the P - F - V_d curves of Figure 12. In our paper, we assume that rainfall antecedent to the high intensity period satisfies depression storage. Such an assumption is necessary if rainfall intensity frequency data such as that of YARNELL [1935] are to be used. If design-storm probability data were available, the entire hydrograph could be estimated with definite advantages. The method presented, however, was designed to help meet the needs of hydrologists by using currently available data. Granted, the infiltration data and the data on hydraulics of flow are not as yet analyzed for this specific purpose; we think that sufficient data are available for analysis to give appreciable assistance to the practicing engineer in his problems. It is a matter of organizing the analysis of such data for a common purpose.

Schiff states that the detention-discharge relationship on the rising side is different from the relationship when determined from the recession side of a hydrograph. The senior author, in 1942, and SHARP, HOLTAN, and MUSGRAVE [1949] found that, if rainfall excess (P - F - V_d) were first proportioned to detention and runoff of overland flow by using the detention-discharge relationship as derived from small plots, this discrepancy was minimized. It also became evident that overland flow was essentially ended when the peak rate occurred at the watershed weir; hence, we did not consider overland flow detentions since the watershed peak rate was the only one determined.

References

SHARP, A. L., H. N. HOLTAN, and GEORGE MUSGRAVE, Infiltration in relation to runoff on small watersheds, U. S. Dept. Agric. SCS-TP-81, June 1949.
YARNELL, DAVID L., Rainfall intensity frequency data, U. S. Dept. Agric. Misc. Pub. 204, 1935.

Corrigendum--On page 774 of the paper as published, the titles of Figures 3 and 4 were inadvertently interchanged. The Figure numbers are correct.--Ed.

Transactions, American Geophysical Union Volume 32, Number 5 October 1951

LETTER TO THE EDITOR

GRADUATE INSTRUCTION IN GEODETIC ENGINEERING

Since membership of the American Geophysical Union's Section of Geodesy is largely derived from those who engage in the practice of geodetic engineering, it is pertinent to consider what opportunities are available for formal academic training at the graduate level in the United States in this one of the geophysical sciences. This query evokes an answer that is easy to formulate for there are few graduate colleges that offer instruction in geodesy or geodetic engineering. This vacuity is hardly the basis for a healthy growth in academic stature for those who find their major activity in teaching surveying nor does it favor an effective and stimulating treatment of the subject in our university classrooms and laboratories.

The writer does not desire to particularize on the statistical portrayal of undergraduate requirements in surveying and mapping in the many civil engineering departments in this country. The best summary to date is that of R. C. BRINKER [A study of summer surveying schools and camps in the United States and Canada, Civ. Eng. Bull. Amer. Soc. Eng. Education, Feb. 1949]. This letter treats primarily of the problem of graduate instruction in geodetic engineering. Furtheremore, a critical evaluation of some of the current philosophies relating to surveying in civil-engineering education is undertaken since they are the important stimuli in molding future educational policies.

For some ten or more years certain leaders in American engineering education have given much attention to the apparent need to produce graduates who are more social minded and more acutely aware of their responsibilities in a changing world. To encourage the future engineer to assume a more articulate role among tomorrow's citizenry and to equip him more efficiently for private and public service, the courses of study have been modified to include training in certain of the social sciences and in the fine arts. Also, new engineering subjects have been introduced. Hence, there has been a decided movement to broaden the educational base by the inclusion of both non-technical and new engineering courses. Regardless of the wisdom or demerit of such action, the impact on the teaching of surveying has been noticeable in two ways. One effect has been a gradual reduction in the amount of instruction devoted to this subject. The second and more severe repercussion has been the relegation of the teaching of surveying to the sub-professional level and the assignment of instructional tasks to the youngest and least-experienced members of the college staffs. This has made it increasingly difficult to develop teaching facilities at the graduate level for effective instruction and training in advanced surveying or geodetic engineering.

There are few special curricula or options providing for major study in surveying and mapping in the undergraduate colleges. Certainly there are none that are experiencing a healthy growth. Dismaying as this may at first seem, the situation is not unexpected nor is it entirely undesirable. The four-year program still being followed at most schools must delimit its objectives so far as subject matter is concerned. In order to produce men who will develop both the ability to become good engineers as well as informed leaders who can help in resolving the difficult social and political problems of a world tense with international strife, the fullest emphasis of educational policy must be upon the attainment of learning capacity rather than upon the acquisition of facts.

The place for instruction in geodetic engineering is in the graduate college despite the excursions that are made into the fields of triangulation, precise leveling, and other advanced fields in extended undergraduate courses in surveying. In the graduate college the interest of those who elect further training can be better sustained through vigorous instruction under more competent instructors.

The teaching of geodesy is virtually non-existent in this country. Only doctoral candidates with a broad background in applied mathematics could be expected to profit from such specialized studies and the lofty level of their achievements might make them the most unacceptable accessions to the staff of a civil engineering department should they choose to enter engineering education. Their future with a federal surveying agency might well depend upon the practical acumen they blend with their academic prowess.

Since the beginning of World War II great changes have been effected in some of the procedures for executing geodetic surveys and the need for better knowledge of the form and dimensions of the spheroid has been frequently asserted. These developments stem from the requirements of our military establishments for better map and survey data for waging global warfare. The refinement of Shoran and other electronic length-measuring devices, the design of new map projections, the transformation of geodetic coordinates from one datum to another, and the study of methods for rapid determination of astronomic position, to mention only a few problems, indicate a fruitful field of endeavor for future geodetic engineers and geodesists.

Summary--Undergraduate instruction in surveying and mapping often borders on decadence because of a paucity of talented teachers who are vocal proponents of the science. This in consequence has affected training in geodetic engineering because the unattractive character of undergraduate instruction has diverted prospective graduate students to other areas of civil engineering.

The military implications of geodesy and geodetic engineering assert the great need for the institution of courses in geodetic engineering in a few graduate colleges at our leading universities.

There is great need to re-vitalize the teaching of surveying by using personable and experienced engineers from our important surveying and mapping agencies on more of our academic staffs. It is believed that this will be instrumental at the impressionable undergraduate level in enabling more of the students to gain a clearer perception of the function served by the geodetic engineer, in providing a more adequate portrayal of the opportunities available in geodetic engineering, and assist in creating a desire for further training in the graduate colleges.

Milton O. Schmidt

University of Illinois,
Urbana, Illinois

UNION, SECTION, AND COMMITTEE ACTIVITIES

INFORMAL REPORT ON THE NINTH GENERAL ASSEMBLY OF THE INTERNATIONAL UNION OF GEODESY AND GEOPHYSICS HELD IN BRUSSELS, BELGIUM, AUGUST 21 TO SEPTEMBER 1, 1951

The Ninth General Assembly of the International Union of Geodesy and Geophysics was held in a friendly and informal atmosphere at the Free University of Brussels from August 21 to September 1, 1951. Registration took place on August 20 and the records of the Organizing Committee show that nearly 700 delegates and over 200 guests were present from some 43 countries as follows: Algeria, Argentina, Australia, Austria, Belgium, Canada, Denmark, Egypt, Finland, France, Germany (Western), Great Britain, Greece, India, Indo-China, Indonesia, Ireland, Israel, Italy, Japan, Kenya, Luxemburg, Morocco, Monaco, The Netherlands, New Zealand, Norway, Pakistan, Peru, Philippines, Portugal, Siam, South Africa, Southern Rhodesia, Spain, Sweden, Switzerland, Tunis, Turkey, United States of America, Uruguay, Venezuela, and Yugoslavia. The United Nations Organization and other international bodies were also represented.

The opening session on August 21 was held in the Palais des Beaux-Arts in the heart of Brussels, was attended by Her Majesty Queen Elizabeth, and was addressed by various dignitaries of the Royal Academy of Sciences, the City of Brussels, and the Belgian Government. Following these addresses, there was a musical interlude prior to the first Plenary Session at which a resumé was given of the activities of the Bureau of the Union since the Eighth General Assembly in Oslo in 1948. In the afternoon the first scientific sessions got under way. The presidential address of Walter D. Lambert (U.S.A.) of the Association of Geodesy was followed by that of President Robert Stoneley of the Association of Seismology. In the late afternoon the group was received in the City Hall of Brussels. This included an inspection of the very interesting old building and its various works of art.

On Wednesday, August 22, the presidential addresses of the other five Associations (Meteorology, J. A. B. Bjerknes; Terrestrial Magnetism and Electricity, Sydney Chapman; Oceanography, H. U. Sverdrup; Volcanology, B. G. Escher; Hydrology, V. Frolow) were presented in order and scientific sessions of the various Associations got under way. Inasmuch as the International Union of Geodesy and Geophysics is not only a Union of National Committees, but is also a Union of seven distinct fields in the Earth sciences, there were frequently as many as seven sessions proceeding simultaneously. Joint sessions were held among the Associations as follows: Exploration of the ocean floor, Seismology and Oceanography (this was noted to be one of the most outstanding sessions of the whole Assembly); Physics of the high atmosphere and the ionosphere, Meteorology and Terrestrial Magnetism and Electricity; Microseisms, Seismology, Meteorology, and Oceanography; Evaporation from the surface of the Earth, Meteorology and Hydrology; and Circulation in the atmosphere and the oceans, Meteorology and Oceanography. Within the various Associations there were symposia, as for example in Meteorology, symposia on Circulation in the atmosphere, Problems of micrometeorology, and Solar radiation.

The discussions at the various meetings were excellent insofar as time permitted. Some of the outstanding values of the meetings were developed through this medium. There were also many informal gatherings in the reception rooms of the Assembly and in the corridors leading to the Association meetings that did much to develop thought in the broad field of geophysics, and to establish firm and friendly relations among scientists of various lands. One of the great benefits of such meetings is that persons who knew of others through their writings became personally acquainted and thus there was a better basis for understanding and discussion than there could possibly have been otherwise.

In advance of the official opening of the Assembly on August 21 there had been, in the previous week, meetings of the Committee on the Physics of the Earth's Interior. Time was found during the Association meetings to continue these on the afternoon of August 28 and the morning of August 29. It is, of course, essential that problems of the Earth's interior be considered in a broad organization of geophysics; yet there was no Association into which these problems fit. There was discussion of the establishment of an eighth association or of joining certain ones, but the solution of this problem was to broaden the Association of Seismology to include the physics of the Earth's interior. This included a formal renaming (now, Seismology and the Physics of the Earth's Interior).

The activity of the General Assembly extended beyond the sessions and the informal discussions in the reception rooms. A number of very interesting and instructive excursions were ar-

Her Majesty Queen Elizabeth receives the Officers of the Union, Presidents of the Associations, and Officers of the Belgian Organizing Committee; front row--Robert Stoneley, L. H. Adams, F. A. Vening Meinesz, Her Majesty Queen Elizabeth, Sydney Chapman, J. F. Cox, J. M. Stagg; back row--V. Frolow, H. U. Sverdrup, N. E. Norlund, J. A. B. Bjerknes, B. G. Escher, Ch. Charlier, and (behind Dr. Stagg) W. D. Lambert (photograph by G. Hersleven)

Chuji Tsuboi, Walter D. Lambert, J. M. Stagg, and Mrs. Stagg at the City Hall of Brussels

J. W. Joyce, Walter H. Bucher, Conrad Thoren, and Eric Schonstedt on the grounds of the Cite Estudiantine, headquarters of the meeting

ranged by the Belgian Committee. The first of these was to Antwerp on August 25. The morning was devoted to various interests and the group was divided into six parts, permitting persons to select as desires dictated, but in the afternoon the groups joined on an excursion that traveled a short distance up the Scheldt Estuary and returned past the beautiful skyline of Antwerp, going down the Scheldt about half way to the Dutch border, and then returning to enter the upper harbor of Antwerp, passing through the lock. The excursion was not only interesting and informative, but offered further opportunity for the many informal and friendly associations for the development of friendships on an international basis.

On Sunday, August 26, there were four excursions. These included an excursion to Liege and Eupen, stressing especially the hydrologic features; an excursion to Liege and Spa, stressing particularly the geologic features; one to Ghent and Bruges, emphasizing hydrologic and oceanographic features; and one to the coal mine region south of Brussels, emphasizing especially seismologic features.

On Tuesday afternoon, August 28, Her Majesty Queen Elizabeth received the members of the Executive Committee and of the Council and their wives at her villa at the Chateau de Laeken. On Thursday afternoon, August 30, there were again a number of excursions, one to the Geophysical Center at Dourbes of especial interest to the Association of Terrestrial Magnetism and Electricity, one of especial interest to Seismology and Volcanology to the coal mine region near Beringen, another to Mons of special interest to seismologists and volcanologists, a visit to the hydraulic laboratory in Antwerp, and to the hydraulic laboratory at the University of Ghent, and a visit to the locks in the vicinity of Mons. There were other excursions within Brussels, such as the ones to the Cartographic Hall of the Royal Library, the Meteorological Observatory, and the Institute of Military Geography.

A special program of excursions was arranged for the ladies and other guests of the delegates, who found themselves no less busy with these interesting trips than the delegates in their sessions.

On August 31 there was a closing dinner held in the Palais des Beaux-Arts which over 800 attended. This was followed by musical entertainment. The closing Plenary Session was held September 1 in the Palais des Beaux-Arts. The General Secretary gave the report of the Council, and the Presidents of the Associations presented their official reports and resolutions. The announcement of election of officers of the Union and the Associations, and expressions of gratitude for services rendered by the Belgian Committee and many other groups, brought the session to a close. The Tenth General Assembly will be held in Italy in 1954.

Of the commendations, three may be mentioned here. First, the General Secretary extended special thanks to the Finance Committee headed by J. Tuzo Wilson for the careful study of the finances of the International Union and its Associations and for its thorough and objective report. (The Committee, which was established at Oslo in 1948, was continued through the next triennium.) Second, the Association of Geodesy in a resolution pointed out the European Triangulation Adjustment, initiated by the Association, as one of the most outstanding international projects ever undertaken by the Union. Special messages of commendation were sent to the Army Map Service and the U. S. Coast and Geodetic Survey for the leading role they played in this undertaking of far-reaching importance. Third, at the opening session, gracious tribute had been paid to Dr. John A. Fleming of the United States and Prof. B. Helland-Hansen of Norway for their outstanding accomplishments in the organization and development of the Union. Their responses to the cable greetings were read at the closing Plenary Session. The results of the elections were as follows:

Union--President, Sydney Chapman (Great Britain); Vice Presidents, J. A. B. Bjerknes (U.S.A.) and Gino Cassinis (Italy); General Secretary, G. Laclavere (France). Finance Committee--Chairman, J. Tuzo Wilson (Canada); Secretary, K. Hilding Beij (U.S.A.); Members, A. T. Doodson (Great Britain), M. M. Goldschmidt (Israel), and Jean Vignal (France).

Geodesy--President, C. F. Baeschlin (Switzerland); Vice Presidents, J. de Graaff-Hunter (Great Britain) and Gino Cassinis (Italy); Secretary, P. Tardi (France); Honorary Presidents (Members of Executive Committee), F. A. Vening Meinesz (The Netherlands) and W. D. Lambert (U.S.A.); Member of Executive Committee, N. E. Nörlund (Denmark). Section of Triangulation--President, C. A. Whitten (U.S.A.); Secretary, Antonio Marussi (Italy). Section of Leveling--President, Paolo Dore (Italy); Secretary, O. Simonsen (Denmark). Section of Geodetic Astronomy--President, J. F. Cox (Belgium); Secretary, H. S. Jelstrup (Norway). Section of Gravity--President, P. Lejay (France); Secretary, B. C. Browne (Great Britain). Section of Geoid--President, Guy Bomford (Great Britain); Secretary, __ __ Thompson (Great Britain).

Seismology and the Physics of the Earth's Interior--President, Beno Gutenberg (U.S.A.); Vice Presidents, Harold Jeffreys (Great Britain) and Pietro Caloi (Italy); Secretary, Jean-Pierre Rothé (France).

Meteorology--President, K. R. Ramanathan (India); Vice Presidents, C.-G. Rossby (U.S.A.) and P. Queney (France); Secretary, Jacques van Mieghem (Belgium); Executive Committee: Walter Mörikofer (Switzerland), Charles Norman (Great Britain), and Viho Väisälä (Finland). Ozone Commission--President, G. M. B. Dobson (Great Britain); Secretary, Charles Normand (Great Britain). Radiation Commission--President, A. Angström (Sweden); Secretary, Walter Mörikofer (Switzerland).

Terrestrial Magnetism and Electricity--President, Jean Coulomb (France); Vice Presidents, J. Bartels (Germany) and Sydney Chapman (Great Britain); Secretary, V. Laursen (Denmark); Executive Committee, Albert A. Giesecke, Jr. (Peru), Joseph Kaplan (U.S.A.), M. Hasegawa (Japan), S. L. Malurkar (India), and J. M. Rayner (Australia).

Oceanography--President, J. Proudman (Great Britain); Vice Presidents, C. O'D. Iselin (U.S.A.) and J. Rouch (France); Secretary, H. Mosby (Norway); Deputy Secretary, R. H. Fleming (U.S.A.); Executive Committee: J. N. Carruthers (Great Britain), H. Pettersson (Sweden), P. Groen (The Netherlands), H. U. Sverdrup (Norway). Committee on Tides--Chairman, H. A. Marmer (U.S.A.); Secretary, J. Proudman (Great Britain); Members, J. E. Fjeldstad (Norway), A. Gougenheim (France), W. Horn (Germany), N. Menendez (Spain), and M. Tenani (Italy). Committee on Mean Sea Level and its Variations--Chairman, J. D. Nares (Monaco); Secretary, R. H. Corkan (Great Britain); Members, L. P. Disney (U.S.A.) and J. Egedal (Denmark). Committee on Nomenclature of Ocean Bottom Features--J. D. H. Wiseman (Great Britain); Secretary, J. D. Nares (Monaco); Members, K. O. Emery (U.S.A.), H. H. Hess (U.S.A.), Ph. H. Kuenen (The Netherlands), and H. Pettersson (Sweden). Committee on Oceanographical Observations from Atlantic Weather Ships--Chairman, J. R. Lumby (Great Britain); Secretary, H. Mosby (Norway); Members, J. Le Gall (France), John Lyman (U.S.A.), F. S. Russell (Great Britain), J. W. Termijtelen (The Netherlands), and H. Thomsen (Denmark). Committee on Preparation of Technical Handbook on Physical Oceanography--Chairman, H. U. Sverdrup (Norway); Members, J. N. Carruthers (Great Britain), G. E. R. Deacon (Great Britain), E. C. La Fond (U.S.A.), H. Mosby (Norway), and N. W. Rakestraw (U.S.A.). Committee on Question Concerning Preparation of a Bibliography--Chairman, H. U. Sverdrup (Norway); Secretary, P. Groen (The Netherlands); Members, H. L. G. Bencker (Monaco), J. N. Carruthers (Great Britain), L. Fage (France), J. R. Lumby (Great Britain), R. B. Montgomery (U.S.A.), R. Revelle (U.S.A.), J. T. Ruud (Norway), and F. Vercelli (Italy).

Volcanology--President, B. G. Escher (The Netherlands); Vice Presidents, L. Glangeaud (France) and Jean Verhoogen (Belgium and U.S.A.); Secretary, F. Signore (Italy).

Hydrology--President, J. Th. Thijsee (The Netherlands); Vice Presidents, Giulio de Marchi (Italy) and A. N. Khosla (India); Secretary, Leon Tison (Belgium). Commission on Surface Waters--President, Ragnar Melin (Sweden); Vice President, Dino Tonini (Italy); Secretary, Louis Serra (France). Commission on Subterranean Waters--President, A. N. Sayre (U.S.A.); Vice President, V. Frolow (France); Secretary, F. Buchan (Great Britain). Commission on Snow and Ice--President, Gerald Seligman (Great Britain); Vice President, R. Haefeli (Switzerland); Secretary, P. D. Baird (Canada). Committee on Land Erosion--President, W. C. Lowdermilk (U.S.A.), Vice President, J. Tixeront (Tunis); Secretary, Carl B. Brown (U.S.A.).

The group from the United States included 124, as follows: Robert Abel; Leason H. Adams and Mrs. Adams; L. B. Aldrich; Arthur J. Arseneault, Jr.; T. S. Austin; Donald M. Baker and Mrs. Baker; James Balsley, Jr.; H. H. Bedke; K. Hilding Beij; Francis Birch; J. A. B. Bjerknes and Mrs. Bjerknes; E. H. Bramhall and Mrs. Bramhall; Walter H. Bucher; Charles R. Burrows; Perry Byerly; Horace R. Byers; Jule Charney; George L. Clarke, Mrs. Clarke, and three children, ages 14 to 19 years; Vernon G. Crudge; John Dail; Dale D. Desper; Robert S. Dietz; L. P. Disney and Mrs. Disney; C. Hewitt Dix and Mrs. Dix; J. A. Duerksen; Hans A. Einstein; Maurice Ewing and Mrs. Ewing; Scott E. Forbush; Bernard F. Foster; Francois N. Frenkiel; Sigmund Fritz; Dave Fultz; William M. Gibson; Albert A. Giesecke, Jr. and Mrs. Giesecke; William E. Gordon; Ross Gunn; Beno Gutenberg and Mrs. Gutenberg; Mrs. Katharine C. Hafstad; George H. Harding; Edw. Hazelwood; Bruce C. Heezen; W. A. Heiskanen; C. V. Hendricks and Mrs. Hendricks; Floyd W. Hough; E. O. Hulburt and Mrs. Hulburt; Woodrow C. Jacobs; H. Freeborn Johnston and Mrs. Johnston; R. D. Johnston; J. Wallace Joyce; Joseph Kaplan and Mrs. Kaplan; Walter D. Lambert; Walter B. Langbein; Rudolph M. Langer; Gunnar Leifson; L. Lek; Walter C. Lowdermilk; John Lyman; Elwyn A. Moseley; J. N. Nanda; Homer E. Newell, Jr.; Frank Neumann; Edward D. Oliver; Helen B. Pettit; Fred B. Phleger, Jr. and Mrs. Phleger; T. J. Putney; Daniel F. Rex, Mrs. Rex, and three children; Franklin E. Roach, Mrs. Roach, and two daughters and one son; C.-G. Rossby; Lynn H. Rumbaugh; Walter E. A. Ruska and Mrs. Ruska; A. Nelson Sayre, Mrs. Sayre, and Miss Elizabeth Sayre; J. Frank Schairer; E. O. Schonstedt; J. Paul Schumacher and Mrs. Schumacher; S. F. Singer; Louis B. Slichter, Mrs. Slichter, and Miss Slichter; Waldo E. Smith; Vernon O. Snead; Franklin F. Snyder; Paul Sollenberger; Kenneth C. Spengler; J. J. Stoker; Howard E. Tatel; Conrad J. Thoren; Richard Tousey, Mrs. Tousey, and Miss Joanna Tousey; F. J. Veihmeyer and Mrs. Veihmeyer; Chas. A. Whitten; George P. Woollard; and S. P. Worden.

Waldo E. Smith

BIBLIOGRAPHY

BIBLIOGRAPHY: GENERAL

ANONYMOUS, Verhandlungen der Schweizerischen Naturforschenden Gesellschaft, v. 129, Lausanne, 418 pp., 1949.

BEDERKE, ERICH, Geophysik der allgemeinen Geologie, Naturforschung und Medezin in Deutschland, 1939-1946, pt. I, pp. 229-237, 1951

CHACKETT, K. F., K^{40} and the age of the atmosphere, Letter in Phys. Rev., v. 81, p. 1057, 1951 [abstr. in Phys. Abstr., v. 54, no. 643, p. 684, 1951].

DOUGUE, MAX, Rapport sur les observations faites par le "Commandant Charcot," au cours de sa croisière dans l'Antarctique durant l'été austral 1948-1949, Serv. Central Hydrogr., Ministère Marine, Paris, 247 pp., 1950.

FERRAZ de CARVALHO, ANSELMO, Estudos de geologia e de geofisica, 143 pp., Coimbra Univ. Pub., 1950 [abstr. in Geophys. Abstr., p. 223, 1950].

GASSMANN, F., Recent geophysical research work, Bull. Assn. Suisse Géol. et Ing. du Pétrole, v. 17, no. 53, pp. 5-14, 1 pl., 1950.

JEFFREYS, H., Dynamic effects of a liquid core, II, Mon. Not. R. Astron. Soc., v. 110, no. 5, pp. 460-466, 1950 [abstr. in Phys. Abstr., v. 54, no. 643, p. 684, 1951].

SATO, T., On the twilight glow over the world, Tohôku Univ. Sci. Rep., Geophysics, v. 3, no. 1, pp. 1-12, 1951. (Has tables and a chart showing seasonal changes in all latitudes.)

BIBLIOGRAPHY: GEODESY

ARGENTINA, INSTITUTO GEOGRÁFICO MILITAR, Annuario, v. 11, years 1947-49, 101 pp., 46 tables, 50 maps, 1950.

BENDEFY, L., Die Rolle der Urmarken des Präzisionsnivellementes des früheren Militär-geographischen Institutes zu Wien bei der Feststellung aktueller Krustenbewegungen, Földtani Közlöny, Budapest, v. 79, no. 9-12, pp. 363-393, 1949.

BENDEFY, L., Lever d'altitude par la méthode des points cotés, Földmerestani Közlemények, Budapest, v. 3, pp. 11-22, 1951 (in Hungarian with summary in French).

BERNASCONI, CARLO, Trasformazioni con mezzi otticomeccanici fra le proiezioni cartografiche della sfera, Geofis. Pura e Applicata, Milano, v. 15, no. 3-4, 11 pp., 1949 (summary in English).

BJERHAMMAR, ARNE, Application of calculus of matrices to method of least squares, with special reference to geodetic calculations, Trans., R. Inst. of Tech., Stockholm, no. 49, 86 pp., 1951.

BJERHAMMAR, ARNE, Rectangular reciprocal matrices, with special reference to geodetic calculations, Bull. Géod., Internat. Assn. Geod., IUGG, v. 20, pp. 188-220, 1951.

BOSSOLASCO, M., and I. GENNARO, La depressione dell'orizzonte marino a Genova, Geofis. Pura e Applicata, Milano, v. 18, 8 pp., 1950 (summary in English).

CHOW, CARL, Gradual developing method, Bull. Géod., Internat. Assn. Geod., IUGG, v. 20, pp. 221-229, 1951.

CORPACIU, ALEXANDRE J., Considérations sur les équations de condition et le calcul des développements des corrélatives dans la compensation conditionnelle des chaînes de quadrilatères avec deux diagonales, Bull. Géod., Internat. Assn. Geod., IUGG, v. 20, pp. 163-169, 1951.

de ALMEIDA CASTRO, JOSÉ, Determinação do meridiano verdadeiro, o I.G.G., São Paulo, v. 5, no. 3, pp. 258-270, 1947.

EGYED, L., The elevation correction of anomalies, Földtani Közlöny, Budapest, v. 79, no. 1-4, pp. 96-111, 1949.

GOUGENHEIM, A., Étude practique de la marée gravimétrique, Bull. Géod., Internat. Assn. Geod., IUGG, v. 20, pp. 170-187, 1951.

HAALCK, H., Über die zweckmässigste Form der Anwendung der Eötvösschen Drehwaage und der Bearbeitung ihrer Messergebnisse, Gerlands Beitr. zur Geophys., Akad. Verlagsgesellschaft Geest and Portig K.-G., Leipzig, v. 62, no. 1, pp. 57-73, 1950.

HALES, A. L., and D. I. GOUGH, Measurements of gravity in southern Africa, 58 pp., 1 pl., 20 pp. tables, 1950.

HARADA, Y., Results of precise levellings along the coast of the Kagosima Bay, Bull. Geogr. Surv. Bur., v. 1, pt. 1, pp. 9-16, 1948 (in Japanese with summary in English).

HEISKANEN, W., On the world geodetic system, Isos. Inst., Internat. Assn. Geod., IUGG, no. 26, 25 pp., 1951.

HERMANSEN, ALFRED, Construction of an instrument intended to give a quick standardization of invar levelling rods, Geod. Inst., Denmark, Med. 24, 18 pp., 1951.

HERRMANN, KARL, Messungen mit dem Zeiss-Opton-Nivellier Ni 2, Vermessungstechnische Rundschau, Hamburg, v. 13, no. 7, pp. 172-176, 1951.

HOMORÓDI, L., Les travaux géodésiques de l'USSR, Földméréstani Közlemények, Budapest, v. 3, pp. 1-11, 1951 (in Hungarian with summary in French).

JAPAN, GEOGRAPHICAL SURVEY BUREAU, GEODETIC SECTION, The measurement of 100 m base line rhombus in the compound of the Tokyo Astronomical Observatory at Mitaka, Bull. Geogr. Surv. Bur., v. 1, pp. 77-79, 1948 (in Japanese with summary in English).

JOWITT, S., Levelling by radar altimeter, Eng. J., Montreal, v. 33, pp. 689-694, 1950 [abstr. in Phys. Abstr., v. 54, no. 638, p. 93, 1951].

KNEISSL, M., and G. STRASSER, Zur Auswahl der Dreiecksketten und Bestimmung der Längen- und Richtungsübertragungsfehler, Bull. Géod., Internat. Assn. Geod., IUGG, v. 20, pp. 123-162, 1951.

MELCHIOR, P. J., On the influence of the law of distribution of density in the Earth's interior on the luni-solar variation of gravity at a point, Geofis. Pura Appl., v. 16, pp. 105-112, 1950 (in French) [abstr. in Phys. Abstr., v. 54, no. 638, p. 171, 1951].

MORELLI, C., Il géoide e la geofisica, Ann. Geofisica, v. 2, no. 2, pp. 251-254, 1949.

MORELLI, C., Rilievo gravimetrico sperimentale nella Zona di Zaule (Trieste), Boll., Soc. Adriatica di Scienze Naturali, Trieste, v. 45, pp. 121-128, 2 tables, 1949-50 (summary in English).

MORELLI, C., Collegamento gravimetrico Padova-Trieste e rilievo gravimetrico regionale del veneto Centro-Orientale, Riv. Geofis. Appl., v. 11, no. 2, 20 pp., 1950 (summary in English).

MORELLI, C., Studio del teodolite Wild T 2 N. 8217, Tecnica Italiana, Riv. Ing. Sci., Trieste, v. 5, no. 5, 6 pp., 1950 (summary in English).

MORELLI, C., Sull'utilizzabilità a scopo geofisico delle relazioni fra anomali eötvössiane e magnetische, Geof. Pura Appl., Milano, v. 18, 7 pp., 1950 (summary in English).

MORELLI, C., Rilievo gravimetrico e riduzione isostatica nell'Italia Nord-Orientale, Riv. Ing. Sci., Trieste, v. 6, no. 3-4, 1951 (summary in English).

MORELLI, C., Rilievo sperimentale gravimetrico-magnetico nell'avampaese dei Colli Euganei, An. Geofis., pt. 1 in v. 3, no. 4, pp. 523-566, 1950; pt. 2 in v. 4, no. 3, 15 pp., 1951.

MORELLI, C., Studio del gravimetro Worden n. 50 e sua applicazione per un rilievo geofisico di dettaglio alle foci del Timavo, An. Geofis., v. 4, no. 2, pp. 247-271, 1951.

MORELLI, C., Triangolazione fondamentale della città di Trieste per la determinazione della posizione delle nuove sedi dell'Universita e dell'Observatorio Geofisico, Tecnica Italiana, Riv. Ing. Sci., Trieste, v. 6, no. 1, 12 pp., 1951 (summary in English).

MUTO, K., T. OKUDA, and Y. HARADA, The land deformation accompanying the Fukui earthquake of June 28, 1948, Bull. Geogr. Surv. Inst., Japan, v. 2, pt. 1, pp. 27-36, 1950.

OKUDA, T., On the mode of the vertical land-deformation accompanying the great Nankaido earthquake of 1946, Bull. Geogr. Surv. Inst., Japan, v. 2, pt. 1, pp. 37-59, 1950.

OMORI, M., Note on the systematic local deviation of the original point of geodetic coordinate in Japan, Bull. Geogr. Surv. Bur., v. 1, pt. 1, pp. 73-75, 1948 (in Japanese with summary in English).

OMOTE, S., Precise leveling at the eastern foot of Volcano Usu, Bull. Earthquake Res. Inst., Tokyo Univ., v. 28, pt. 1-2, pp. 133-142, 1950.

SAVELIEFF, S., Les horloges à quartz et à diapason, Bull. Géod., Internat. Assn. Geod., IUGG, v. 20, pp. 230-246, 1951.

SCHEFFER, V., Elevation corrections of gravity-meter surveys executed in mountainous regions, Földtani Közlöny, Bull. Hungarian Geol. Soc., v. 77, pp. 12-21, 1947 (in Hungarian with summary in English).

SCHÜTZ, G., Das Geodätische Institut, 75 Jahre (1876-1951), Geodätisch-Kulturtechnische Abteilung, Univ. Bonn, 39 pp., 1951.

SMITH, N. J., The case for gravity data from boreholes, Geophysics, v. 15, pp. 605-636, 1950 [abstr. in Phys. Abstr., v. 54, no. 638, p. 172, 1951].

SOLAINI, L., and M. CUNIETTI, Rilievo gravimetrico del Comune di Milano, Riv. Geof. Appl., v. 12, no. 1, pp. 1-13, 1951 (summary in English).

SZENES, K., Piquetage à l'aide du calcul des surfaces, Földméréstani Közlemények, Budapest, v. 3, pp. 27-36, 1951 (in Hungarian with summary in French).

VINCZE, V., L'augmentation de la précision des stadimètres avec mire verticale, Földméréstani Közlemények, Budapest, v. 3, pp. 22-27, 1951 (in Hungarian with summary in French).

BIBLIOGRAPHY: METEOROLOGY

ARAKAWA, H., Aerological observations made in the "Kitty Typhoon" by the Central Meteorological Observatory, Tokyo, Papers in Met. Geophys., Met. Res. Inst., Tokyo, v. 1, no. 2-4, pp. 217-221, 1950.

ARAKAWA, H., Rossby-Haurwitz's equation for the conservation of vertical vorticity component in the baroclinic atmosphere, Papers in Met. Geophys., Met. Res. Inst., Tokyo, v. 1, no. 2-4, pp. 173-174, 1950.

ARAKAWA, H., The conservation law about the horizontal of the total vorticity, Papers in Met. Geophys., Met. Res. Inst., Tokyo, v. 1, no. 2-4, pp. 170-172, 1950.

ARAKAWA, H., The vorticity equations in orthogonal curvilinear coordinates, Papers in Met. Geophys., Met. Res. Inst., Tokyo, v. 1, no. 2-4, pp. 165-169, 1950.

BANERJE, B. M., and R. ROY, A time base circuit for a high precision ionospheric sounding apparatus, Indian J. Phys., v. 24, pp. 411-419, 1950 [abstr. in Phys. Abstr., v. 54, no. 641, p. 457, 1951].

BAUR, F., Latest discoveries of main weather features, Scientia, v. 85, no. 10, pp. 241-251, 1950 (in German) [abstr. in Phys. Abstr., v. 54, no. 639, p. 255, 1951].

BAUR, F., Tatsachen zur Frage der Vorbereitung des mitteleuropäischen Winter, An. Met., Hamburg, v. 3, no. 11-12, pp. 352-360, 1950 (summary in English).

BERLYAND, O. S., On the theory of the distribution of temperature in the Earth's atmosphere, Izv. Ser. Geograf. Geofiz., v. 13, pp. 388-392, 1949 (in Russian) [abstr. in Appl. Mech. Rev., v. 4, no. 2, p. 132, 1951].

BERLYAND, O. S., A more exact theory of the diurnal variation of the temperature of the atmosphere taking account of the variability of the coefficient of turbulent heat exchange during the course of the day, Izv. Ser. Geograf. Geofiz., v. 14, pp. 79-81, 1950 (in Russian) [abstr. in Appl. Mech. Rev., v. 4, no. 2, p. 132, 1951].

BOWEN, E. G., Radar observations of rain and their relation to mechanisms of rain formation, J. Atmos. Terr. Phys., v. 1, no. 3, pp. 125-140, 1951 [abstr. in Phys. Abstr., v. 54, no. 641, p. 459, 1951].

BREWER, A. W., and R. H. DOBSON, An automatic frost-point hygrometer for measurements in the upper air, Inst. Elect. Engrs., Paper 1104, 4 pp., 1951 [abstr. in Phys. Abstr., v. 54, no. 639, p. 254, 1951].

CHAPMAN, S., Upper atmospheric nomenclature, J. Atmos. Terr. Phys., v. 1, no. 3, p. 201, 1951 [abstr. in Phys. Abstr., v. 54, no. 641, p. 458, 1951].

DEACON, E. L., Radiative heat transfer in the air near the ground, Aust. J. Sci. Res. Ser. A, v. 3, no. 2, pp. 274-283, 1950 [abstr. in Appl. Mech. Rev., v. 4, no. 6, p. 389, 1951].

DESSENS, H., Some remarks on the study of the microphysics of natural clouds, Cent. Proc. R. Met. Soc., pp. 59-60, 1950 [abstr. in Phys. Abstr., v. 54, no. 642, p. 569, 1951].

DOBSON, G. M. B., Physics of clouds and precipitation, Cent. Proc. R. Met. Soc., pp. 34-36, 1950 [abstr. in Phys. Abstr., v. 54, no. 642, p. 569, 1951].

EFFENBERGER, ERNST, Messmethoden zur Bestimmung des CO_2 - Gehaltes der Atmosphäre und die Bedeutung derartiger Messungen für die Biometeorologie und Meteorologie, pt. 1, Messmethoden, An. Met., Hamburg, v. 3, no. 11-12, pp. 321-328, 1950 (summary in English).

FAEGRI, K., On the value of paleoclimatological evidence, Cent. Proc. R. Met. Soc., pp. 188-195, 1950 [abstr. in Phys. Abstr., v. 54, no. 642, p. 570, 1951].

FAUST, HEINRICH, Die synoptischen Bedingungen für das Entstehen der Unwetterfront vom 22.7.1948 über Nordbayern, Ber. Deutsch. Wetter., US Zone, no. 19, Bad Kissingen, pp. 29-32, 1950.

FUKUOKA, A., A study on 10-day forecast (a synthetic report), Geophys. Mag., Central Met. Observ., Tokyo, v. 22, no. 3, pp. 177-208, 1951.

FULTZ, DAVE, Experimental studies related to atmospheric flow around obstacles, Proc. First Internat. Meeting on Alpine Met., Ist. Geofis. Italiano, Milano, pp. 8-13, 1950.

GAMBO, K., The criteria for stability of the westerlies, Geophys. Notes, Tokyo Univ., v. 3, no. 29, 13 pp., 1950.

GERSON, N. C., and J. KAPLAN, Nomenclature of the upper atmosphere, J. Atmos. Terr. Phys., v. 1, no. 3, p. 200, 1951 [abstr. in Phys. Abstr., v. 54, no. 641, p. 458, 1951].

GOLDIE, A. H. R., The average planetary circulation in vertical meridian planes, Cent. Proc. R. Met. Soc., pp. 175-187, 1950 [abstr. in Phys. Abstr., v. 54, no. 642, p. 567, 1951].

GOODY, R. M., The experimental determination of the thermal state of the lower stratosphere, Cent. Proc. R. Met. Soc., pp. 9-18, 1950 [abstr. in Appl. Mech. Rev., v. 4, no. 5, p. 323, 1951].

HAUER, A., A new recording raingauge, J. Sci. Instr., v. 28, pp. 84-85, 1951 [abstr. in Phys. Abstr., v. 54, no. 641, p. 457, 1951].

HOVMÖLLER, E., Zonal and meridional air currents in the stratosphere over Europe, Proc. First Internat. Meeting on Alpine Met., Ist. Geofis. Italiano, Milano, pp. 32-40, 1950.

HUMPHRIES, J., The Earth's atmosphere, J. Brit. Interplan. Soc., v. 10, pp. 18-26, 1951 [abstr. in Phys. Abstr., v. 54, no. 641, p. 457, 1951].

INOUE, EIICHI, On the temperature fluctuations in a heated turbulent fluid, Geophys. Notes, Tokyo Univ., v. 3, no. 34, 5 pp., 1950.

ISONO, K., and Y. HUZIWARA, Improved code sending type radiosonde, Papers in Met. Geophys., Met. Res. Inst., Tokyo, v. 1, no. 2-4, pp. 299-312, 1950.

KASAHARA, A., On the distribution of the amount of rainfall and filling-up of the "Kitty-Typhoon," Geophys. Notes, Tokyo Univ., v. 3, no. 30, 6 pp., 1950.

KIVELIOVITCH, M., On the vertical wind component, J. Sci. Mét., v. 1, pp. 18-22, 1949 (in French) [abstr. in Appl. Mech. Rev., v. 4, no. 2, p. 133, 1951].

KRYSTANOV, L., A case of the enlargement of cloud drops by fusion, Dokl. Akad. Nauk SSSR, v. 76, no. 1, pp. 53-56, 1951 (in Russian) [abstr. in Phys. Abstr., v. 54, no. 641, p. 459, 1951].

LEPPIK, EGON, Die Sturmfluten in der Elbmündung in der ersten Hälfte des 20. Jahrhunderts, Besondere Mitt. Deutsch. Gemmässerkundlichen Jahrbuch, no. 1, in two parts, Wasser- und Schiffahrts., Hamburg, 51 pp. (pt. 1); 63 pp., tables and figures (pt. 2), 1950.

LUDLAM, F. H., Structure of shower clouds, Nature, London, v. 167, pp. 254-256, 1951 [abstr. in Phys. Abstr., v. 54, no. 642, p. 569, 1951].

MAGATA, M., On the structure of the jet stream, Papers in Met. Geophys., Met. Res. Inst., Tokyo, v. 1, no. 2-4, pp. 175-187, 1950.

MARTYN, D. F., Cellular atmospheric waves in the ionosphere and troposphere, Proc. R. Soc., London, Ser. A, v. 201, no. 1065, 216-234, 1950 [abstr. in Appl. Mech. Rev., v. 4, no. 3, p. 197, 1951].

MATSUMOTO, S., On the coupling between upper waves and surface pressure centers, Papers in Met. Geophys., Met. Res. Inst., Tokyo, v. 1, no. 2-4, pp. 198-205, 1950.

MITRA, A. P., Tides in the ionosphere, Indian J. Phys., v. 24, pp. 387-404, 1950 [abstr. in Phys. Abstr., v. 54, no. 641, p. 458, 1951].

MIYAKE, Y., and Y. SUGIURA, The mechanism of dissolution of the atmospheric chloride into rain water, Papers in Met. Geophys., Met. Res. Inst., Tokyo, v. 1, no. 2-4, pp. 222-226, 1950.

MONIN, A. S., Dynamic turbulence in the atmosphere, Izv. Akad. Nauk SSSR, Ser. Geograf. Geofiz., v. 14, pp. 232-254, 1950 (in Russian) [abstr. in Appl. Mech. Rev., v. 4, no. 5, p. 322, 1951].

MÜLLER-ANNEN, HANS, Zur Prognose der Zugbahnen von Tiefdruckgebieten, pt. 1, Zugbahnen und Geschwindigkeit der Tiefdruckgebiete, An. Met., Hamburg, v. 3, no. 11-12, pp. 341-351, 1950 (summary in English).

OGURA, Y., On the atmospheric turbulence (I), Geophys. Notes, Tokyo Univ., v. 3, no. 26, 8 pp., 1950.

PEKERIS, C. L., Free oscillations of an atmosphere in which temperature increases linearly with height, Nat. Adv. Comm. Aero Tech., Note 2209, 24 pp., 1950 [abstr. in Appl. Mech. Rev., v. 4, no. 3, p. 195, 1951].

PETTERSSEN, S., Some aspects of the general circulation of the atmosphere, Cent. Proc. R. Met. Soc., pp. 120-155, 1950 [abstr. in Appl. Mech. Rev., v. 4, no. 6, p. 387, 1951].

PRIESTLY, C. H. B., On the dynamics of the general atmospheric circulation, Aust. J. Sci. Res., Ser. A, v. 3, pp. 1-18, 1950 [abstr. in Appl. Mech. Rev., v. 4, no. 5, p. 322, 1951, and in Phys. Abstr., v. 54, no. 638, p. 174, 1951].

ROBINSON, G. D., Two notes on temperature changes in the troposphere due to radiation, Cent. Proc. R. Met. Soc., pp. 26-29, 1950 [abstr. in Appl. Mech. Rev., v. 4, no. 6, p. 389, 1951].

SCHNEIDER-CARIUS, K., Lo strato base dell'atmosfera come determinante il clima della Alpi, Proc. First Internat. Meeting on Alpine Met., Ist. Geofis. Italiano, Milano, pp. 14-23, 1950 (summary in German).

SIOTANI, MASAO, On the fluctuation of the vertical component of wind velocity in the air layer near the ground, J. Met. Soc., Japan, v. 27, no. 10, pp. 295-303, 1949 (in Japanese) [abstr. in Appl. Mech. Rev., v. 4, no. 2, p. 134, 1951].

SYŌNO, SIGEKATA, On the vortical rain, Geophys. Notes, Tokyo Univ., v. 3, no. 25, 3 pp., 1950.

THAMS, J. C., Misure della radiazione solare diretta a diverse altezze nel versante meridionale delle Alpi, Proc. First Internat. Meeting on Alpine Met., Ist. Geofis. Italiano, Milano, pp. 41-46, 1950 (summary in English).

TSUJI, M., On the rate of evaporation of water drops, J. Met. Soc. Japan, v. 28, no. 4, pp. 119-121, 1950 (in Japanese) [abstr. in Appl. Mech. Rev., v. 4, no. 5, p. 324, 1951].

VENKITESHWARAN, S. P., Winds at 10 km and above over India and its neighborhood, Memoirs, India Met. Dept., v. 28, pt. 2, pp. 55-120, 78 pl., 1950.

VINACCIA, G., L'urbanistica e la climatologia alpina: la scelta dei luoghi da edificare in montagna, Proc. First Internat. Meeting on Alpine Met., Ist. Geofis. Italiano, Milano, pp. 158-165, 1950 (summary in English).

BIBLIOGRAPHY: TERRESTRIAL MAGNETISM AND ELECTRICITY

ABELÉS, FLORIN, Recherches sur la propagation des ondes électromagnetiques sinusoidales dans les milieux stratifiés, An. Phys., v. 5, pp. 596-640, 1950 [abstr. in Geophys. Abstr., p. 248, 1950].

AGARWALA, K. S., The mobility of the small ions of the atmosphere at Poona, Indian J. Met. Geophys., v. 2, pp. 63-65, 1951 [abstr. in Phys. Abstr., v. 54, p. 571, 1951].

AGOSTINELLI, C., Influence of the solar magnetism on the motion of rotation of the Earth, Geofis. Pura Appl., v. 18, no. 1, pp. 18-37, 1950 (in Italian) [abstr. in Phys. Abstr., v. 54, p. 383, 1951].

ALFVÉN, H., The theory of magnetic storms and auroras, letter in Nature, v. 167, p. 984, 1951. (Comments on D. F. Martyn paper with same title, v. 167, pp. 92-94, with response by Martyn. For subsequent response by S. Chapman, see v. 168, p. 86, 1951.)

AL'PIN, L. M., The theory of dipole sounding, Gostoptekhizdat, Moscow, 88 pp., 1950 (in Russian) [abstr. in Geophys. Abstr., p. 35, 1951].

ANONYMOUS, The Kodaikanal Observatory (1901-1950), Indian J. Met. Geophys., v. 2, pp. 85-95, 1951.

ARGENCE, É., Sur des expressions approchées de l'indice de réfraction d'un milieu ionisé soumis à l'action du champ magnétique terrestre, C.-R. Acad. Sci., Paris, v. 232, pp. 2080-2082, 1951.

BANERJEE, B. M., and R. ROY, A time base circuit for a high precision ionospheric sounding apparatus, Indian J. Phys., v. 24, pp. 411-419, 1950 [abstr. in Phys. Abstr., v. 54, p. 457, 1951].

BARTELS, J., Tägliche erdmagnetische Charakterzahlen 1884-1950 und planetarische dreistundliche erdmagnetische Kennziffern Kp 1932/33 und 1940-1950 (Beobachtungen über geophysikalische Wirkungen der Sonne und der Mondes, Mitt. 1), Göttingen, Akad. Wiss., Mat.-Phys. Kl., Sonderheft, 29 pp., 1951. (Has added leaf, Erdmagnetische Kennziffern Kp bis 23. April 1951.)

BIBL, K., The ray path in a curved ionospheric layer, Rev. Sci., Paris, v. 88, pp. 27-29, 1950 (in French) [abstr. in Phys. Abstr., v. 54, p. 425, 1951].

BOCK, R., Atlas of magnetic declination of Europe for epoch 1944.5, Army Map Service, Corps of Engineers, Washington, D. C., 12 pp., 69 isogonic charts, 75 miscellaneous charts, 8 figs., 1951.

BUDDE, W., Investigations of the spreading of sky waves, Zs. Naturforsch., v. 5a, pp. 683-687, 1950 (in German) [abstr. in Phys. Abstr., v. 54, p. 567, 1951].

CABANNES, J., Influence des orages magnétiques sur la region F2, C.-R. Acad. Sci., Paris, v. 232, pp. 2125-2127, 1951.

CARDUS, J. O., On the phase law in Earth currents, Rev. Geofís., v. 9, pp. 215-233, 1950 (in Spanish) [abstr. in Geophys. Abstr., p. 7, 1951, and in Phys. Abstr., v. 54, p. 372, 1951].

CARON, J., and R. VEILLITH, Relations entre l'activité solaire et quelques phénomènes terrestres, Urania, v. 35, pp. 170-171, 1950. (Note acknowledging Pödder's priority on semiannual variation in magnetic activity.)

CHAPMAN, S., The Earth's magnetism and its changes, Indian J. Physics, v. 24, no. 9, and Indian Assoc. Cultiv. Sci., Proc., v. 33, no. 9, pp. 1-16, 1950.

COVINGTON, A. E., Some characteristics of 10.7-cm solar noise, I and II, J. R. Astr. Soc. Canada, v. 45, pp. 15-22 and 49-61, 1951.

DAVIDSON, D., Reflexion of high frequencies during auroral activity, Nature, v. 167, pp. 277-278, 1951 [abstr. in Phys. Abstr., v. 54, p. 461, 1951].

de VAUCOULEURS, G., Observations of twilight discontinuities, C.-R. Acad. Sci., Paris, v. 232, pp. 342-344, 1951 (in French) [abstr. in Phys. Abstr., v. 54, p. 374, 1951].

DIZER, M., On an apparent Earth-effect on sunspot activity, Istanbul Univ. Fen. Fak. Mec., Ser. A, v. 15, pp. 205-211, 1950 [abstr. in Phys. Abstr., v. 54, p. 270, 1951]. (Criticizes Clough's findings.)

ELLISON, M. A., Ionospheric effects of solar flares, Pub. R. Obs. Edinburgh, v. 1, no. 4, pp. 53-72, 1950 [abstr. in Phys. Abstr., v. 54, p. 458, 1951].

FERRELL, Oliver P., Enhanced trans-equatorial propagation following geomagnetic storms, Nature, v. 167, pp. 811-812, 1951.

FOSS, H., and L. VEGARD, Continued investigations on the excitation functions of nitrogen bands, Avh. Norske Videns. Akad. Oslo, I, Mat.-Nat. Kl., no. 4, 14 pp., 1949 [abstr. in Phys. Abstr., v. 54, p. 571, 1951].

FRITSCH, VOLKER, Some geophysical investigations by radio methods using the procedure of substituted capacity and the determination of the direction of propagation in the vicinity of a transmitter, and possibility of indirect determination of deep electrical discontinuities, Archiv. für Met., Geophys., Bioklim., Ser. A, v. 2, no. 1, pp. 127-143, 1950 (in German) [abstr. in Geophys. Abstr., p. 36, 1951].

GARTLEIN, C. W., Protons and the aurora, letter in Nature, v. 167, p. 277, 1951 [abstr. in Phys. Abstr., v. 54, p. 461, 1951; see similar letter in these Transactions, v. 32, p. 120, 1951].

GÉHÉNIAU, J., The singular functions of the Klein-Gordon equation, taking account of an external magnetic field, Physica, v. 16, pp. 822-830, 1950 (in French) [abstr. in Phys. Abstr., v. 54, p. 387, 1951].

GERSON, N. C., Ionospheric research in the U. S. Air Force, Proc. Conf. Ionos. Res., Geophys. Res. Papers No. 7, Air Force Cambridge Res. Labs., pp. 136-142, December 1950.

GERSON, N. C., Sporadic E movements, Geofis. Pura Appl., v. 18, no. 1, pp. 162-169, 1950 [abstr. in Phys. Abstr., v. 54, no. 642, p. 566, 1951].

GERSON, N. C., Correlation of auroras with increased cosmic-ray intensities (November 19, 1949), Nature, v. 167, pp. 894-895, 1951.

GERSON, N. C., Radio observations of the aurora on November 19, 1949, Nature, v. 167, pp. 804-805, 1951.

GERSON, N. C., Sporadic E movements on 21 June 1949, Tellus, v. 3, pp. 56-59, 1951.

GIORGI, M., and Others, Regional magnetic survey of the Marche region for the establishment of a central magnetic observatory, An. Geofis., v. 3, pp. 143-171, 1950 (in Italian) [abstr. in Geophys. Abstr., p. 222, 1950].

GLEISSBERG, W., The mean sunspot curve, Istanbul Univ. Obs. Yaz., no. 41, 1951 (in German) [abstr. in Phys. Abstr., v. 54, p. 467, 1951].

GLEISSBERG, W., and A. KIRAL, Prediction of the coming sunspot minimum, Zs. Astrophys., v. 28, pp. 17-27, 1950 (in German) [abstr. in Phys. Abstr., v. 54, p. 270, 1951].

GROVES, A. W., Results of magnetometric survey at Benallt manganese mine, Caernarvonshire, Inst. Min. Met., Trans., London, v. 56, pp. 475-513, 1950 [abstr. in Geophys. Abstr., p. 30, 1951].

HAALCK, H., New views on the cause of the permanent magnetic field of the Earth, Geofis. Pura Appl., v. 18, no. 1, pp. 132-142, 1950 (in German) [abstr. in Phys. Abstr., v. 54, no. 642, p. 565, 1951].

HARDTWIG, E., Mathematical problems in geophysics, An. Geofis., v. 3, pp. 315-335, 1950 (in German) [abstr. in Phys. Abstr., v. 54, p. 371, 1951].

HOLLER, H. D., The role of current distribution in cathodic protection, J. Res., U. S. Nat. Bur. Stds., v. 47, pp. 1-6 (RP no. 2220), 1951.

HOLMES, C. R., Magnetic fields associated with igneous pipes in the central Ozarks, Min. Eng., v. 187, pp. 1143-1146, 1950 [abstr. in Geophys. Abstr., p. 31, 1951].

HUMPHRIES, J., The Earth's atmosphere, J. Brit. Interplan. Soc., v. 10, pp. 18-26, 1951 [abstr. in Phys. Abstr., v. 54, p. 457, 1951].

KALMAN, V. S., Peculiarities of the distribution of stray currents of a traction main line, Elektrichestvo, no. 11, pp. 33-37, 1950 (in Russian).

KATO, YOSHIO, On the magnetic moment of the residual magnetism of the rock, Tohôku Univ. Sci. Rep., Geophys., v. 3, no. 1, pp. 45-47, 1951.

KATO, YOSHIO, Investigation of the magnetic disturbance by the induction magnetograph, Tohôku Univ. Sci. Rep., Geophysics, v. 3, no. 1, pp. 40-44, 1951. (Refers to magnetic storms.)

KATO, YOSHIO, and T. KANNO, On the variations of the cosmic-ray intensity associated with the magnetic storm, Sci. Reports, Geophys., Tohôku Univ., v. 2, pp. 153-157, 1950. (Assumes the effect due to enhancement of ring current.)

KELSO, J. M., The effect of the Lorentz polarization term on the vertical incidence absorption in a deviating ionosphere layer, Proc. Conf. Ionos. Res., Geophys. Res. Papers no. 7, Air Force Cambridge Res. Labs., pp. 72-95, December 1950.

KHASTGIR, S. R., and P. M. DAS, Periodic fading of short-wave radio signals, Proc. Phys. Soc., London, Ser. B, v. 63, pp. 924-930, 1950 [abstr. in Phys. Abstr., v. 54, p. 374, 1951].

KIRKPATRICK, C. B., The influence of vertical ionic drift on a "Chapman region," Austr. J. Sci. Res., Ser. A, v. 1, pp. 423-442, 1948.

KIYONO, T., Theoretical study on the ground resistivity method of electrical prospecting, Mem. Fac. Eng., Kyoto Univ., v. 12, pp. 29-59, 1950 [abstr. in Phys. Abstr., v. 54, no. 641, p. 456, 1951].

KONDORSKII, E. I., The theory of magnetic properties of conglomerates and powdered substances, Izv. Akad. Nauk SSSR, Ser. Geog. Geofiz., v. 14, no. 4, pp. 294-301, 1950 (in Russian) [abstr. in Geophys. Abstr., p. 220, 1950].

KOSHIKAWA, Y., Magnetic survey in the area of topographical deformation of Volcano Usu, Tokyo Univ. Earthquake Res. Inst. Bull., v. 27, pt. 1-4, pp. 21-25, 1949 [abstr. in Geophys. Abstr., p. 223, 1950].

KOTESWARAM, P., Physical properties of the upper atmosphere over India, Indian J. Met. Geophys., v. 2, pp. 101-112, 1951.

KWAL, B., On the electromagnetic radiation of cosmic protons in the intense magnetic fields of celestial objects, J. Phys. Radium, v. 12, pp. 66-67, 1951 (in French) [abstr. in Phys. Abstr., v. 54, p. 467, 1951].

LEJAY, P., and D. LEPECHINSKY, Formation des couches ionisées, influence de la temperature, C.-R. Acad. Sci., Paris, v. 232, pp. 2058-2061, 1951.

MACHIN, K. E., Distribution of radiation across the solar disk at a frequency of 81.5 mc/s, Nature, v. 167, pp. 889-891, 1951.

MACHT, H., Neuere ausländische Arbeiten auf erdmagnetischem Gebiet, Deutsche Hydrogr. Zs., v. 4, pp. 65-71, 1951.

MEEK, J. H., Sporadic ionization at high latitudes, Proc. Conf. Ionos. Res., Geophys. Res. Papers No. 7, Air Force Cambridge Res. Labs., pp. 96-104, December 1950.

MEYER, O., On a special type of magnetic bay, Deutsche Hydrogr. Zs., v. 4, pp. 61-65, 1951 (in German with summary in English).

MISAKI, M., A method of measuring the ion spectrum, Papers in Met. and Geophys., Tokyo, v. 1, pp. 313-318, 1950. (Refers to the mobility spectrum of atmospheric ions.)

MITRA, A. P., Tides in the ionosphere, Indian J. Phys., v. 24, pp. 387-404, 1950 [abstr. in Phys. Abstr., v. 54, p. 458, 1951].

MITRA, S. K., Atomic nitrogen in auroras, Nature, v. 167, p. 897, 1951.

MONTGOMERY, C. C., Counters for cosmic rays, Yale Univ., Sloane Phys. Lab., 80 pp., 1949 [abstr. in U. S. Off. Tech. Serv. Bibliogr. Tech. Rep., v. 15, p. 145, PB 102810, 1951].

MORELLI, C., New criteria in magnetic investigations, An. Geofis., v. 3, pp. 349-355, 1949 (in Italian) [abstr. in Geophys. Abstr., p. 220, 1950 and in Phys. Abstr., v. 54, p. 372, 1951].

MUKHINA, G. V., The screening effect of conductive layers, Izv. Akad. Nauk SSSR, Ser. Geog. Geofiz., v. 14, no. 4, pp. 302-316 and no. 5, pp. 392-402, 1950 (in Russian) [abstr. in Geophys. Abstr., p. 248, 1950, and p. 36, 1951].

MURPHY, THOMAS, Provisional values for magnetic declination in Ireland for the epoch 1950.5, Geophys. Bull., Dublin Inst. Adv. Studies, no. 2, 3 pp., 1 pl., 1951.

NAKABAYASHI, K., and T. FUJIWARA, Generating mechanism of the spontaneous polarization, classification of the generating mechanism, single electrode potential of ores, Tokyo Res. Inst. Natural Resources, Rep. 13, p. 16, 1949, and Rep. 15, pp. 6-16, 1950 (in Japanese with summary in English) [abstr. in Geophys. Abstr., p. 36, 1951].

NICHOLSON, G. F., An introduction to the rationalized M. K. S. system of units, Brit. J. Appl. Phys., v. 2, pp. 177-182, 1951.

O'MALLEY, T., Exploration needed in Peace River by aeromagnetic survey, Petrol. Eng., v. 22, no. 11, pp. B36-B42, 1950 [abstr. in Geophys. Abstr., p. 31, 1951].

OOSIMA, KÔITI, Pri ebleco de loka neegaleco de la taga variado de la tera magnetismo, Sci. Reports, Geophys., Tohôku Univ., v. 2, no. 3, pp. 202-205, 1950 (abstr. in English).

PAETZOLD, H. K., A determination of the vertical distribution of atmospheric ozone by the aid of lunar eclipses, Zs. Naturforsch., v. 5a, pp. 661-666, 1950 (in German) [abstr. in Phys. Abstr., v. 54, p. 566, 1951].

PETERSON, ALLEN M., The interpretation of long scatter echo patterns, Proc. Conf. Ionos. Res., Geophys. Res. Papers No. 7, Air Force Cambridge Res. Labs., pp. 58-71, December 1950.

PFISTER, WOLFGANG, Effect of the D-ionospheric layer on very low frequency radio waves, Proc. Conf. Ionos. Res., Geophys. Res. Papers No. 7, Air Force Cambridge Res. Labs., pp. 107-135, December 1950.

POUND, R. V., and W. D. KNIGHT, A radio-frequency spectrograph and simple magnetic-field meter, Rev. Sci. Insts., v. 21, pp. 219-225, 1950. (Covers range from about 100 to 25,000 oersteds, using the principle of nuclear resonance.)

PRICE, A. T., Recent theories of the Earth's magnetic field, R. Coll. Sci., Sci. J., v. 20, pp. 125-138, 1949 [abstr. in Geophys. Abstr., p. 5, 1951].

PYASKOVSKAYA-FESENKOVA, Y. V., Asymmetry in the atmospheric indicatrix of scattering of light, Dokl. Akad. Nauk SSSR, v. 73, pp. 287-290, 1950 (in Russian). (Pertains to relation of scattering to wavelength.)

RATCLIFFE, J. A., and Others, Winds and turbulence in the upper atmosphere, Nature, v. 167, pp. 626-628, 1951. (Report of a geophysical discussion held at the Royal Astronomical Society.)

ROCARD, Y., On a mechanism of coronal radio emission, C.-R. Acad. Sci., Paris, v. 232, pp. 598-600, 1951 (in French) [abstr. in Phys. Abstr., v. 54, p. 467, 1951].

von ROKA, E. G., On an indirect influence of solar activity on the intensity of cosmic rays, Zs. Naturforsch., v. 5a, pp. 517-530, 1950 (in German) [abstr. in Phys. Abstr., v. 54, p. 323, 1951].

ROSE, D. C., The cosmic-ray observatory at Ottawa, Nature, v. 168, pp. 269-271, 1951.

SATO, Y., Mathematical study of the propagation of waves upon stratified medium, Bull. Earthquake Res. Inst., v. 26, pp. 1-4, 1948,

SCHILLING, G. F., and H. SEPER, On the dependence of atmospheric electrical potential gradients on the metropolitan location of Vienna, Arch. Met. Geophys. Bioklimat., Ser. A, v. 2, pp. 334-341, 1950 [abstr. in Phys. Abstr. (from Met. Abstr.), v. 54, p. 460, 1951].

SHKLOVSKII, I. S., The possibility of determining the distance to "point" sources of radio waves of the galaxy, Dokl. Akad. Nauk SSSR, v. 73, pp. 479-482, 1950 (in Russian).

SHKLOVSKII, I. S., Identification of the infrared emission of the night sky with the vibration-rotation lines of the hydroxyl OH molecule, Dokl. Akad. Nauk SSSR, v. 75, pp. 371-374, 1950 (in Russian) [abstr. in Phys. Abstr., v. 54, p. 460, 1951].

SHULEIKIN, V. V., The magnetic field of the Earth and the world oceans, Dokl. Akad. Nauk SSSR, v. 76, pp. 57-60, 1951 (in Russian).

SIMAMURA, H., and I. ICHIMURA, On the intensities and altitudes of the night-sky light, Met. Res. Inst., Papers in Met. Geophys., v. 1, pp. 153-162, 1950.

SLEPIAN, J., Lines of force in electric and magnetic fields, Amer. J. Phys., v. 19, pp. 87-90, 1951 [abstr. in Phys. Abstr., v. 54, p. 501, 1951].

STANLEY, J. P., Ionospheric reflection of very long radio waves, Canad. J. Res. A, v. 28, pp. 549-557, 1950 [abstr. in Phys. Abstr., v. 54, p. 425, 1951].

STEHBERGER, K. H., An "electrical nose" for the continuous observation of atmospheric aerosols, Deutsch. Wetterd. US-Zone, Berichte, no. 12, pp. 171-176, 1950 (in German) [abstr. in Phys. Abstr., v. 54, p. 566, 1951].

TIKHONOV, A. N., Determining the electrical characteristics of the deep layers of the Earth's crust, Dokl. Akad. Nauk SSSR, v. 73, pp. 295-298, 1950 (in Russian). (Pertains to magnetic variations and possible use of earth currents.)
TRUEMAN, A. E., Report of the Geological Survey Board [Great Britain] for the year 1949, 18 pp., 1950 [abstr. in Geophys. Abstr., p. 31, 1951].
TSCHU, K. K., On the practical determination of lunar and luni-solar daily variations in certain geophysical data, Austr. J. Sci. Res., Ser. A, v. 2, pp. 1-24, 1949. (A simplified explanation of the Chapman-Miller method.)
TU, CHENG YEH, Some measurements of the atmospheric electric potential over Mei-tan, J. Chinese Geophys. Soc., v. 2, pp. 147-157, 1950.
VERNOV, S. N., and A. M. KULIKOV, The angular distribution of cosmic rays in the stratosphere, Dokl. Akad. Nauk SSSR, v. 73, pp. 483-486, 1950 (in Russian).
VON ARX, WILLIAM S., Dead reckoning by surface current observation, J. Inst. Navig. (London), v. 4, pp. 117-125, 1951.
VON ARX, WILLIAM S., An electromagnetic method for measuring the velocities of ocean currents from a ship under way, Mass. Inst. Tech. - Woods Hole Oceanogr. Inst., Papers in Phys. Oceanog. and Met., v. 11, no. 3, 1950
WASIUTYNSKI, J., Studies in hydrodynamics and structure of stars and planets, Astrophys. Norveg., v. 4, 497 pp., 1946 [abstr. in Phys. Abstr., v. 54, p. 469, 1951].

BIBLIOGRAPHY: OCEANOGRAPHY

ARMSTRONG, F. A. J., The determination of silicate in sea water, J. Mar. Biol. Assn., v. 30, pp. 149-160, 1951.
BAILEY, W. B., and H. B. HACHEY, The vertical temperature structure of the Labrador Current, Proc. Nov. Scot. Inst. Sci., v. 22, pt. 4, pp. 34-48 (1949-1950), 1951.
BAILEY, W. B., and H. B. HACHEY, An increasing Atlantic influence in Hudson Bay, Proc. Nov. Scot. Inst. Sci., v. 22, pt. 4, pp. 17-33 (1949-1950), 1951.
COOPER, L. H. N., Research in oceanography, Nature, v. 168, pp. 184-185, 1951.
DEUTSCHES HYDROGRAPHISCHES INSTITUT, Jahresbericht no. 4, 70 pp., 11 pl., Hamburg, 1950; no. 5, 72 pp., 11 pl., 1951.
DIETRICH, G., Influences of tidal streams on oceanographic and climatic conditions in the sea as exemplified by the English Channel, Nature, v. 168, pp. 8-11, 1951.
ERICSON, D. B., MAURICE EWING, and BRUCE C. HEEZEN, Deep-sea sands and submarine canyons, Bull. Geol. Soc. Amer., v. 62, pp. 961-966, 1951.
FUKUSHIMA, NAOSHI, Progressive changes in the current system of the bay disturbance, Geophys. Notes, Geophys. Inst., Tokyo Univ., v. 3, no. 22, 10 pp., 1950.
GREEN, F. H. W., Tidal phenomena with special reference to Southampton and Poole, Dock Harb. Auth., v. 32, pp. 143-148, 154, 1951.
HIDAKA, KOJI, and SHIGEO HIKOSAKA, Note on the Hawaiian tsunami of April 1, 1946, J. Ocean. Soc. Japan, v. 5, pp. 19-31, 1946 (in Japanese) [abstr. in Appl. Mech. Rev., v. 3, no. 11, p. 390, 1950].
HIKOSAKA, SHIGEO, On the diffraction of tidal waves by an island with irregular boundary, J. Ocean. Soc. Japan, v. 5, pp. 32-37, 1949 (in Japanese) [abstr. in Appl. Mech. Rev., v. 3, no. 11, p. 390, 1950].
JAPAN, HYDROGRAPHIC BUREAU, Oceanographic phenomena in Izu Shoto and approaches in 1947, Hydrog. Bull., no. 8, pp. 31-32, 2 pl., 1948 (in Japanese).
JAPAN, HYDROGRAPHIC BUREAU, Distribution of sea ice in the northern Japan Sea, Hydrog. Bull., no. 8, pp. 33-42, 11 pl., 1948 (in Japanese).
KNAPP, ROBERT T., Model studies of Apra harbor, Dock Harb. Auth., v. 31, pp. 367-371; v. 32, pp. 9-14, 60-64, 81-86, 125-129, 155-159, 1951.
LA FOND, E. C., Processing oceanographic data, U. S. Hydrographic Office, H. O. Pub. No. 614, 114 pp., Washington, 1951.
LACOMBE, H., Les marées de la Manche, Bull. Inst. Océan, no. 989, 24 pp., 19 fig., 1951.
LADD, HARRY S. (Chm.), Report of the Committee on a Treatise on Marine Ecology and Paleoecology, 1949-1950, Div. Geol. Geogr., Nat. Res. Coun., 59 pp., 1950.
LEGENDRE, RENE, Les resources énergétiques de la mer, Bull. Inst. Océan, no. 947, 16 pp., 1949.
MIYAKE, Y., The possibility and the allowable limit of formation of air bubbles in the sea, Pap. Met. Geophys., v. 2, no. 1, pp. 95-101, 1951.
NANNICHI, T., On the fluctuation of the Kurosiwo and Oyasiwo, Pap. Met. Geophys., v. 2, no. 1, pp. 102-112, 1951.
POLLI, SILVIO, Le maree all'isola de S. Andrea nell'Adriatico centrale, An. Geofis., v. 3, pp. 515-521, 1950.
POLLI, SILVIO, Ricerche di fotometria subacquea nelle acque della laguna di Venezia, Ist. di Studi Adriatici Pub. no. 2, Venezia, 13 pp., 1950.

REVELLE, ROGER, and K. O. EMERY, Barite concretions from the ocean floor, Bull. Geol. Soc. Amer., v. 62, pp. 707-724, 1951.
SHEPARD, FRANCIS P., Photography related to investigation of shore processes, Photogrammetric Engineering, v. 16, pp. 756-769, 1950.
SHEPARD, FRANCIS P., Submarine canyons: a joint product of rivers and submarine processes, Science, v. 114, pp. 7-9, 1951.
U. S. HYDROGRAPHIC OFFICE, Sonic soundings, H. O. Pub. no. 606-b, 13 pp., Washington, 1950.
U. S. HYDROGRAPHIC OFFICE, Bathythermograph observations, H. O. Pub. no. 606-c, 13 pp., Washington, 1951.
U. S. HYDROGRAPHIC OFFICE, Sea and swell observations, H. O. Pub. no. 606-e, 8 pp., Washington, 1950.
VAN RIEL, P. M., H. C. HAMAKER, and L. VAN EYCK, Oceanographic results; tables, Snellius Exped., Leiden, v. 2, pt. 6, 44 pp., 1950.
VEEN, P. CH., Surface salinities in the Indonesian Archipelago and adjacent waters, Organization for Scientific Research in Indonesia, Djakarta O.S.R. Pub. 33, 20 pp., c. 1950.
WOODFORD, A. O., Stream gradients and Monterey sea valley, Bull. Geol. Soc. Amer., v. 62, pp. 799-852, 1951.

BIBLIOGRAPHY: VOLCANOLOGY

AGARD, J., Sur l'age et le mode de gisement des aiounites et mestigmerites du Maroc Oriental, Notes Serv. Géol., Notes et Mém. 76, v. 3, pp. 189-195, 1950.
ANDERLE, NIKOLAUS, Zur Schichtfolge und Tektonik des Dobratsch und seine Beziehung zur Alpin-dinarischen Grenzzone, Jb. Geol. Bundesanstalt, Wien, Festband, 1949-1951, v. 94, pp. 195-236, 1950.
BEDERKE, E., Über den Wärmehaushalt der Regionalmetamorphose, Geol. Rundschau, v. 35, no. 1, pp. 26-32, 1947.
BEDERKE, E., Grundfragen des Vulkanismus, Geol. Rundschau, v. 35, no. 2, pp. 127-133, 1948.
Bederke, E., Kennzeichen magmatischer Granite, Nach. Akad. Wissens., Göttingen, Math.-Phys. Klasse 1949 Math.-Phys.-Chem. Abteilung, pp. 27-32, 1949.
CARLÉ, W., Neue Beobachtungen zur Deckgebirgstektonik von Südwest Deutschland, Jahresberichte und Mitt. Oberrheinischen Geol. Vereines, v. 32, n.s., pp. 10-33, 1943-50.
COTELO NEIVA, J. M., Geochemical prospecting, Estudos, notas e trabalho serv. fomento mineiro (Portugal), v. 5, pp. 91-98, 1950 [abstr. in Chem. Astr., v. 45, no. 6, p. 2374, 1951].
DELECOURT, J., Application de la notation équivalentaire à l'étude des analyses des roches éruptives, Bull. Soc. Belge Géol., v. 59, no. 1-2, pp. 80-93, 1951.
GEORGALAS, G. C., and J. PAPASTAMATIOU, Über den Ausbruch des Santorinvulkanes von 1939-1941, der Ktenas-Ausbruch (zweite vorläufige Mitteilung), Bull. Vol., Internat. Assn. Volcanology, IUGG, v. 11, Ser. 2, pp. 3-37, 21 pl., 1951.
HANTKE, GUSTAV, Übersicht über die vulkanische Tätigkeit 1941-1947, Bull. Vol., Internat. Assn. Volcanology, IUGG, v. 11, Ser. 2, pp. 161-208, 2 pl., 1951.
IKEDA, NAGAO, Geochemical studies on the hot springs of Arima, I, General observations, J. Chem. Soc., Japan, Pure Chem. Sect., v. 70, pp. 328-329, 1949 [abstr. in Chem. Abstr., v. 45, no. 7, p. 3101, 1951].
JUNG, K., The temperature-gradient at the Earth's surface and the radioactive heat production in the Earth's crust taking into account the half-lives, Geofis. Pura Appl., v. 17, pp. 1-12, 1950 (in German) [abstr. in Phys. Abstr., v. 54, no. 639, p. 253, 1951].
KIMURA, KENJIRO, and Others, Chemical prospecting, III, Chemical studies on the natural waters of the Hitachi Mine district; IV, Chemical prospecting at the southern part of the Sado gold mine, the distribution of minute amounts of silver and copper in rocks, J. Chem. Soc. Japan, Pure Chem. Sect., v. 71, pp. 464-467, 1950 [abstr. in Chem. Abstr., v. 45, no. 14, 6130 g-i, 1951].
MIHOLIĆ, STANKO, A geochemical method of prospecting for ore deposits, Intern. Geol. Congr., Rep. 18th Session, Gt. Brit., v. 42, pt. 2, p. 8719b, 1948 [abstr. in Chem. Abstr., v. 45, no. 5, p. 1919, 1951].
MINAKAMI, T., Recent activities of Volcano Usu (V), Topographical deformations during the 1943-1945 eruption, Bull. Earthquake Res. Inst., Tokyo Univ., v. 28, pt. 1-2, pp. 143-152, 2 pl., 1950.
MINAKAMI, TAKESHI, and Others, The 1944 eruption of Volcano Usu in Hokkaido, Japan, Bull. Vol., Internat. Assn. Volcanology, IUGG, v. 11, Ser. 2, pp. 45-157, 25 pl., 1951.
MINAKAMI, T., and Others, Recent activities of Volcano Usu (VI), Precise leveling around Mt. Usu in 1949, Bull. Earthquake Res. Inst., Tokyo Univ., v. 28, pt. 1-2, pp. 153-160, 1 pl., 1950.
MORET, LÉON, Les idées nouvelles sur l'origine des chaines de montagnes, Travaux Lab. Géol., Univ. Grenoble, v. 28, pp. 1-56, 1950 (1951).
NYTKO-BOCHENSKA, J., Contribution à la petrographie des montagnes de Hnilec, An. Soc. Géol. Pologne, v. 20, no. 1-2, pp. 101-116, 1950.

OPPENHEIM, VICTOR, The Volcano Puracé, Amer. J. Sci., v. 248, pp. 171-179, 1950.
OSBORNE, G. D., The Kuttung vulcanicity of the Hunter-Karuah District with special reference to the occurrence of Ignimbrites, J. and Proc. R. Soc. New South Wales, v. 83, pt. 4, pp. 288-301, 1950.
RUBIO, A., Notas sobre geología de Panamá, Univ. Panamá, 183 pp., 1949.
RUNCORN, S. K., Heat flow in the Earth, Nature, London, v. 166, pp. 974-976, 1950 [abstr. in Phys. Abstr., v. 54, no. 640, p. 372, 1951].
SIEGEL, A., Diabase exotique dans le Crétacé des Karpates, An. Soc. Géol. Pologne, v. 20, Fasc. 1-2, pp. 159-164 (in Polish with summary in French, 1950.
TANAKADATE, HIDEZO, Proposal (Oslo Assembly - August 1948), Bull. Vol., Internat. Assn. Volcanology, IUGG, v. 11, Ser. 2, pp. 41-43, 4 pl., 1951. (Concerns studies of Volcano Usu.)
TANEDA, S., "Ball Andesite" from Ushio, South Kyushu, Japan, Mem. Fac. Sci. Kyūsyū Univ., v. 3, ser. D, no. 2, pp. 63-70, 1949.
TANEDA, S., Some relations between chemical composition and optical properties in hornblende and biotite, Mem. Fac. Sci. Kyūsyū Univ., v. 3, no. 2, pp. 1-13, 1949.
TANEDA, S., Studies on volcanoes in Japan and silica content of lavas, J. Japan Assn. Min. Pet. Econ. Geol., v. 33, pp. 129-135, 1949 [abstr. in Chem. Abstr., v. 45, no. 9, 3773i, 1951].
van BEMMELEN, R. W., The origin of igneous rocks in Indonesia, Geol. en Mijnbouw, v. 12, pp. 207-220, 1950 [abstr. in Chem. Abstr., v. 45, no. 9, 3775e, 1951].
WILLIAMS, HOWEL, Volcanoes of the Parícutin region, Mexico, U. S. Geol. Surv. Bull. 965-B, pp. 165-279, 1950 [abstr. in Chem. Abstr., v. 45, no. 6, p. 2376, 1951].
WINKLER, H. G. F., Der Kristallisationsverlauf in einem tholeiit-basaltischen Magma und seine petrogenetische Bedeutung, Abh. Akad. Wissenschaften, Göttingen, Math.-Phys. Klasse, v. 3, no. 24, 1949.

BIBLIOGRAPHY: HYDROLOGY

BENHAM, A. D., The estimation of extreme flood discharges by statistical methods, Proc. New Zealand Inst. Eng., v. 36, 1950, pp. 119-187.
CHILDS, E. C., and N. COLLIS-GEORGE, The permeability of porous materials, Proc. R. Soc. London, Ser. A, v. 201, pp. 1066, 392-405, 1950 [abstr. in Appl. Mech. Rev., v. 4, no. 3, p. 193, 1951].
DENNIS, P. E., and Others, Geology and ground-water resources of parts of Cass and Clay Counties, North Dakota and Minnesota, N. Dak. Geol. Surv., Ground-Water Studies, v. 11, pp. 1-177, 1949 [abstr. in Chem. Abstr., v. 45, no. 6, p. 2609, 1951].
DENNIS, P. E., and Others, Ground water in the Wyndmere area, Richland County, North Dakota, N. Dak. Geol. Surv., Ground-Water Studies, v. 13, pp. 1-59, 1949 [abstr. in Chem. Abstr., v. 45, no. 6, p. 2609, 1951].
FRIEDRICH, WILHEM, Über die Verdunstung vom Erdboden, Zusammenfassender Bericht über die Eberswalder Lysimetermessungen, Das Gas- und Wasserfach, v. 91 (Wasser), 8 pp., 1950.
FRIEDRICH, WILHEM, Die Bedeutung von Lysimeterversuchen, für die Grundwasserkunde, Sonderdruck, Deutscher Verein, Gas- und Wasserfachmännern, 4 pp., 1950.
FRITSCH, V., Einige geoelektrische Untersuchungen auf österreichischen Gletschern, Proc. First Internat. Meeting on Alpine Met., Ist. Geofis. Italiano, Milano, pp. 130-133, 1950 (summary in English).
GARAVEL, M., Observations glaciologiques: l'ablation, en 1950 sur le glacier de Sarenne, Proc. First Internat. Meeting on Alpine Met., Ist. Geofis. Italiano, Milano, pp. 134-137, 1950 (summary in English).
GRAHMANN, RUDOLF B., Witterung und Grundwasser im Bundesgebiet, während des Abflussjahres 1949 und des Winters 1949/50, Das Gas- und Wasserfach, v. 91 (Wasser), 4 pp., 1950.
GRANT, A. P., Soil conservation in New Zealand, Proc. New Zealand Inst. Eng., v. 36, pp. 269-313, 1950.
KIRKHAM, DON, Potential flow into circumferential openings in drain tubes, J. Appl. Phys., v. 21, no. 7, pp. 655-660, 1950 [abstr. in Appl. Mech. Rev., v. 4, no. 4, p. 257, 1951].
LAIRD, WILSON M., and P. D. AKIN, Ground water in the Zeeland area, North Dakota, N. Dak. Geol. Surv., Ground-Water Studies, v. 12, pp. 1-38, 1948 [abstr. in Chem. Abstr., v. 45, no. 6, p. 2609, 1951].
LASSEN, LEON, and Others, Some fundamental plant-soil-water relations in watershed management, Forest Service, U. S. Dept. of Agriculture, 75 pp., 1951 (processed).
LEARMONTH, A. T. A., The floods of 12th August, 1948, in South East Scotland, Univ. of Liverpool, Liverpool, Scotland, 1949 (processed).
LEOPOLD, LUNA B., Vegetation of southwestern watersheds in the nineteenth century, Geogr. Rev., v. 41, pp. 295-316, 1951.
LOHR, ALFRED, Über die Schwierigkeit der Niederschlagsbestimmung im Hochgebirge, Sonderheft, Die Wasserwirtschaft, pp. 7-11, 1950.

MERCANTON, P. L., Sur le developpment de la Glaciologie Suisse, Proc. First Internat. Meeting on Alpine Met., Ist. Geofis. Italiano, Milano, pp. 124-129, 1950.
NATERMANN, ERNST, Die Linie des langfristigen Grundwassers und die Trockenwetterabflusslinie (TWL), Sonderheft, Die Wasserwirtschaft, pp. 12-14, 1950.
PEGUY, M., Caractéristiques hydrologiques de l'année 1948: Précipitations et écoulement, Annuaire Hydrol. France, Soc. Hydrotech. France, pp. 49-64, 1949.
POLLI, S., Stato attuale del ghiacciaio del Mandrone (Adamello) e fattori climatici, Proc. First Internat. Meeting on Alpine Met., Ist. Geofis. Italiano, Milano, pp. 144-149 (summary in English).
POLLI, S., Sul sistema: precipitazione, ghiaccio, deflusso, Proc. First Internat. Meeting on Alpine Met., Ist. Geofis. Italiano, Milano, pp. 141-143, 1950 (summary in English).
RAFFO, JOSÉ MARÍA, Pronóstico de las crecientes del Río Parana, Meteoros, Serv. Met. Nacional, Buenos Aires, no. 1, pp. 91-98, 1951 (summary in English).
REMENIERAS, G., L'hydraulique des stations limnimétriques pour la mesure du débit des cours d'eau, Annuaire Hydrol. France, Soc. Hydrotech. France, pp. 9-48, 1949.
SCHMUCK, ADAM, W sprawie metod pomiarów parowania w Polsce (On the methods of measurement of evaporation in Poland), Sprawozdania, Wroclawskiego Towarzystwa Naukowego, v. 5, no. 1, 14 pp., 1950.
SCHROEDER, _., Die Wasserversorgung in der wasserwirtschftlichen Rahmenplanung, Sonderdruck, Deutscher Verein, Gas- und Wasserfachmännern, 4 pp., 1950.
STEINHAUSER, F., Untersuchungen über die Schneedeckenverhaltnisse in Hochgebirge nach Beobachtungen auf der Grossglockner-Hochalpenstrasse, Proc. First Internat. Meeting on Alpine Met., Ist. Geofis. Italiano, Milano, pp. 103-118, 1950 (summary in English).
VANNI, M., Le variazioni recenti dei ghiacciai italiani ed i loro fattor meteorologici, Proc. First Internat. Meeting on Alpine Met., Ist. Geofis. Italiano, Milani, pp. 150-153, 1950 (summary in English).
VAN RINSUM, ANTON, Die Auswertung von Abflussmessungen, Sonderheft, Die Wasserwirtschaft, pp. 1-3, 1950.
VAN RINSUM, ANTON, Die gewässerkundliche Statistik an den geschiebeführenden Flüssen einschliesslich der Schwerstofftechnik, Sonderheft, Die Wasserwirtschaft, pp. 4-7, 1950.
VIBERT, A., Water motion in soil; new considerations on the discharge of a free underground water level flowing into a well or a drain, Génie Civ., v. 76, no. 9, pp. 160-165, 1949 (in French) [abstr. in Appl. Mech. Rev., v. 4, no. 3, p. 194, 1951].
WAGNER, HUBERT, Abwasserlastpläne als Hilfsmittel der wasserwirtschaftlichen Planung, Sonderheft, Die Wasserwirtschaft, pp. 20-25, 1950.

BIBLIOGRAPHY: TECTONOPHYSICS

CAMPBELL, J. D., Some aspects of rock folding by shearing deformation, Amer. J. Sci., v. 249, pp. 625-639, 1951.
CLARK, R. H., and D. B. McINTYRE, The use of the terms pitch and plunge, Amer. J. Sci., v. 249, pp. 591-599, 1951.
GASSMANN, FRITZ, Über die Elastizität poröser Medien, Viertelj. der Naturfors. Gesells., Zurich, v. 96, 23 pp., 1951 (summary in English).
HABIB, P., Determination of the modulus of elasticity of rocks on the site, An. Inst. Tech. Bat. Trav. Publics, v. 145, pp. 27-35, 1950 (in French) [abstr. in Appl. Mech. Rev., v. 4, no. 7, p. 434, 1951].
KOARK, HANS J., Zur tektonisch-petrographischen Analyse der Kalkbrüche bei Burträsk in Västerbotten, Geol. Fören. Stockholm Förh., v. 73, no. 2, pp. 261-299, 1951.
SOKOLOWSKI, STANISLAW, Les Tatry Bielskie: La géologie de leurs versantes méridionaux, Trav., Serv. Géol. Pologne, v. 4, 56 pp., 11 pl., 1950.
TOMBA, ANNA MARIA, Studio petrografico e strutturale dei gessi metamorfici della zona dello Stelvio, Acta Geol. Alpina Inst. Min. and Petr., Univ. Bologna, v. 3, 21 pp., 5 pl., 1950.

NOTES AND PERSONALIA

NOTES

Portable geodimeter of high precision--A modified geodimeter, developed by E. Bergstrand of Sweden, was demonstrated at the Ninth General Assembly of the IUGG in Brussels recently. While the principles of this device are described in Arkiv för Fysik, v. 2, no. 15, the modified design facilitates portability and permits the measurement of distances along a light path up to a length of 30 km. The accuracy on such distances is claimed to be on the order of three cm, or one in a million. Correction must be made for temperature and refraction. Using frequencies varying by one per cent of the main frequency permits direct determination of the distance.

Coral atoll research program--A six-man expedition of scientists is making a study of Anotoa Atoll in the Southern Gilberts. This is a part of the extensive atoll research program of the Pacific Science Board of the National Research Council in cooperation with the Office of Naval Research, the Army, the Coast Guard, and other agencies.

Continuing seminar in geophysics--The biweekly seminars of the Geophysics Research Division of the Air Force Cambridge Research Center are continuing. The following programs have been announced: November 2, 1951, George S. Benton of Johns Hopkins University, Transfer of water vapor by the atmosphere; November 16, 1951, Jane Rothe of the Center, Multiple solutions of nonlinear functional equations. The seminars are held in Room 1-390 of Massachusetts Institute of Technology, starting at 15h.

New Italian bibliography of hydraulics--Number 1 of a new publication, Idraulica Bibliografia Italiana, covering Italian publications in hydraulics (including some aspects of hydrology and oceanography) was first issued for the period January-March 1950 by Centro di Documentazione Idraulica, Via Loredan 16, Padua, Italy. The successive quarterly numbers, through March 1951, are now available. The publication is in Italian, and includes abstracts.

New Oceanographic Institute of Florida State University--Florida State University has announced the establishment of an Oceanographic Institute, incorporating in the Institute the Alligator Point Marine Laboratory on the upper Gulf Coast of Florida established in 1948, and the Marine Laboratory at Mayport on the upper Atlantic Coast of Florida established in 1949. Graduate assistantships are available in the various phases of the work.

Second Alaskan Science Conference--The Second Alaskan Science Conference was held at Mount McKinley National Park, Alaska, September 4-8, 1951. More than 200 were in attendance, and 93 papers dealing with various aspects of Alaskan science were presented. The Alaska Division of the American Association for the Advancement of Science was organized and installed.

Meeting of the Geological Society of Japan--The Fifty-Eighth Annual Meeting of the Geological Society of Japan was recently held in Kyoto. A number from the United States attended, including Helen L. Foster, Sherman K. Neuschel, and Allen H. Nicol.

Rocky Mountain Hydraulic Laboratory--The Sixth Annual Meeting of the Rocky Mountain Hydraulic Laboratory was held at Allenspark, Colorado, August 18, 1951. In addition to business matters, three scientific papers bearing on hydrology and hydraulics were presented.

Conference on Interfacial Phenomena and Nucleation--A Conference on Interfacial Phenomena and Nucleation was held at Boston University under the joint sponsorship of the University and the Geophysical Research Division of the Air Force Cambridge Research Center August 21-25, 1951. About fifty scientists from five countries were present. Twenty-five papers were presented, a number bearing on important aspects of geophysics, especially meteorology.

Course in underground hydrology at the University of California--A graduate course in underground hydrology is being offered in the fall of 1951 in the Division of Civil Engineering and Irrigation of the University of California in Berkeley. The course is under the direction of T. R. Simpson, and will cover the various aspects of ground-water occurrence, behavior, and development.

PERSONALIA

Kenneth E. Andrews is now engaged as an engineer with the Radio Corporation of America, Victor Division, in Camden, N. J.

Waldemere Bejnar has taken his doctorate in geology at the University of Arizona and is now on duty in Nigeria, West Africa, under the Point Four program of the Economic Cooperation Administration, working with the Nigerian Geological Survey in the lead-zinc district near Abakaliki, Eastern Province.

Henry Todd Bingham, who recently received his Master of Science degree in geophysics at Saint Louis University under the Air Force training program, is now on permanent duty as a Major at the headquarters of the U. S. Air Force in Washington, D. C.

Norman L. Bowen of the Geophysical Laboratory, Carnegie Institution of Washington, has been awarded an honorary degree of Doctor of Science by Yale University.

Percy W. Bridgman of Harvard University has been awarded an honorary degree of Doctor of Science by Yale University.

Edward L. Corton, Jr. is now working as a meteorologist in marine climatology in the U. S. Navy Hydrographic Office.

Richard H. Fleming has resigned his position as Chief of the Division of Oceanography, U. S. Navy Hydrographic Office, and has taken up duties as Executive Officer of the Department of Oceanography of the University of Washington.

Louis Herman, who has been a Visiting Fellow at the Geophysical Institute of the University of Alaska, has returned to his regular work at the Astrophysical Observatory of the University of Paris. At the Geophysical Institute he was working on auroral spectroscopy, some of the results of which appear in a paper in this issue of the Transactions. His studies here were made possible under the provisions of the Fulbright Act, the Air Force Cambridge Research Center, and the University of Alaska.

R. A. Hirvonen, successor to W. Heiskanen as Professor of Geodesy at the Institute of Technology in Helsinki, is on leave from his work in Finland and is associated with the Mapping and Charting Research Laboratory and the newly organized Institute of Geodesy, Photogrammetry, and Cartography at Ohio State University.

Serge A. Korff, Professor of Physics at New York University, recently served as a delegate from the United States to the Fifth South American Congress of Chemistry, at which he presented a paper on Geiger counters. He also delivered a series of lectures at the University of Chile, and was elected an honory member of the faculty.

Helmut E. Landsberg has resigned his duties as Executive Director of the Committee on Geophysics and Geography of the Research and Development Board and is now serving as a Director of the Geophysical Research Division, Air Force Cambridge Research Center.

Martin A. Mason, until recently Chief of the Engineering and Research Branch and Chief Engineer of the Beach Erosion Board, has been named Dean of the School of Engineering of George Washington University.

Edward McCrady, until recently Chief of the Biology Division of the Atomic Energy Commission, has accepted the Presidency of the University of the South at Sewanee, Tennessee.

Gerhard Neumann of the Geophysical Institute of the University of Hamburg has taken up duties as Visiting Associate Professor of Oceanography at New York University. He will also spend some time at Woods Hole Oceanographic Institution.

Richard W. Rutowski has returned to the Navy as a Lieutenant Commander, serving as a meteorological research officer in the Undersea Warfare Branch of the Office of Naval Research in Washington, D. C.

Francis J. Turner, Professor of Geology at the University of California, has been awarded the Hector Memorial Medal and prize for 1951 by the Royal Society of New Zealand for his outstanding work in metamorphic petrology.

Theodore von Karman of California Institute of Technology has been awarded an honorary degree of Doctor of Science by Yale University.

Boris A. Bakhmeteff, Professor of Civil Engineering at Columbia University since 1931, died at his summer home in Brookfield, Conn., July 21, 1951 at the age of 71. He was born in Tiflis, Russia. He took his degree in civil engineering in 1903 at St. Petersburg, studied at the Polytechnic Institute of Zurich the following year, and took the Doctor of Engineering degree from the Polytechnic Institute of St. Petersburg in 1911, where he taught from 1905 to 1917. He undertook consulting work, specializing in water power, from 1907 to 1915, and served on various commissions from Russia to the United States during World War I, serving as the Ambassador from the Provisional Kerensky Government from 1917 to 1922. Since 1923 he engaged in consulting engineering with headquarters in New York, and in various commercial enterprises. His extensive writings included the classic Hydraulics of Open Channels published in 1932. His influence in recent developments in hydraulics and hydrology was great. He had been a member of AGU since 1934.

ADDITIONS TO THE MEMBERSHIP OF THE AMERICAN GEOPHYSICAL UNION MARCH 11 TO SEPTEMBER 10, 1951

Abel, Mr. Robert B., 3129 Parkway Terrace Dr., S.E., Washington 20, D. C. (e)
Acker, Mr. Richard C., 2827 Saint Paul St., Baltimore 18, Md. (abdfgh)
Adler, Mr. L., 5057 Angus Drive, Vancouver, B. C., Canada (ad)
Afshar, Dr. F. A., 3512 Rittenhouse St., N.W., Washington 15, D. C. (abcdefgh)
Alexander, Lt. R. J., USN, 52 E. 16th St., Paterson 4, N. J. (ae)
Ali, Mr. Hamzah, Mines and Geological Survey, Khairatabad, Hyderabad 14, South India (g)
Anderson, Mr. C. F. W., 2001 South Rd., Baltimore 9, Md. (d)
Anderson, Mr. Olaf, Redmond, Ore. (cg)
Andrews, Mr. Alfred W., 1903 - 23rd St., S.E., Washington 20, D. C. (d)
Arseneault, Lt. Arthur J., Jr., USN, 26 Jackson St., Sanford, Me. (eg)
Ashburn, Mr. Edward V., 100 B Ellis, China Lake, Calif. (c)
Ayres, Mr. James E., 2812 Erie St., S.E., Washington 20, D. C. (abde)
Back, Mr. William, U. S. Geological Survey, 2520 Marconi Ave., Sacramento 15, Calif. (cegh)
Baginsky, Mr. Walter, Apt. 8, 3108 Parkway Terrace Dr., S.E., Washington 20, D. C. (ceg)
Barnes, Dr. Kenneth K., Dept. of Agricultural Engineering, Purdue University, Lafayette, Ind. (g)
Bassett, Mr. Allen M., 21 W. Lawnwood Ave., Orangeburg, N. Y. (fh)
Beach, Mr. Arthur R., Loveridge Circle East, Eau Gallie, Fla. (d)
Belluigi, Prof. Arnaldo, Terugia-Trepo, Italy (bf)
Berry, Mr. Frederick A. F., 2703 Yale Sta., New Haven, Conn. (be)
Best, Capt. William J., USAF, 5209 Jamieson Ave., St. Louis 9, Mo. (bc)
Bingham, Major Henry Todd, Headquarters USAF, Attn: AFOAT-1, The Pentagon, Washington 25, D. C. (bc)
Blagbrough, Mr. John W., c/o Mr. Wilkinson, 1065 James St., Syracuse, N. Y. (ef)
Boggess, Lt. L. J., 3136 Parkway Terrace, Suitland, Md. (cdef)
Borgerd, Mr. William F., International Harvester Co., U. S. Route 41, Evansville, Ind. (g)
Boswell, Lt. Ernest H., 816 Field Artillery Bn., Camp Polk, La. (acdgh)
Bourgeois, Mr. Feodor, 60 E. 94th St., New York 28, N. Y. (fgh)
Bourget, Mr. Sylvio J. H., Soils Dept., University of Wisconsin, Madison 6, Wis. (g)
Branden, Mr. Frederick, 1494 Edgewood St., N.E., Warren, Ohio (c)
Brennan, Mr. D. F., Geophysical Service, Inc., Mayerthorpe, Alta., Canada (bdfh)
Briggs, Dr. Louis I., Jr., Dept. of Geology, University of Michigan, Ann Arbor, Mich. (bcfh)
Brunot, Mr. Kenneth E., 143 E. Chapman Ave., Fullerton, Calif. (e)
Buchanan, Mr. George S., 1964 West Gray, Houston 19, Texas (efh)
Burgunker, Mr. Mark E., 2647 E. 21st St., Brooklyn 35, N. Y. (abcdefgh)
Bush, Mr. Wm. H., Oklahoma Geological Survey, Norman, Okla. (g)
Callahan, Miss Rita C., 83 Brottle St., Cambridge, Mass. (d)
Carlson, Dr. William S., University of Vermont, Burlington, Vt. (cg)
Carman, Mr. Max F., Jr., 10904 Culver Blvd., Culver City, Calif. (abdfh)
Carnahan, Mr. Robert L., Civil Engineering Dept., Johns Hopkins University, Baltimore 18, Md. (cg)
Carroll, Mr. Gerald V., Dept. of Geology, Trinity College, Hartford 6, Conn. (fh)
Casey, Mr. Thomas B., 1508 Holmes Ave., Springfield, Ill. (g)
Cermak, Prof. Jack E., 722 Remington St., Fort Collins, Colo. (ag)
Chase, Mr. George H., 4141 Sequoiah Rd., Apt. 4, Brookhaven, Ga. (gh)
Chatfield, Mr. Benjamin V., 208 Wakeman Rd., Fairfield, Conn. (g)
Christensen, Mr. Eddie G., 6399 Thomas St., Kansas City 3E, Mo. (ceg)
Christensen, Dr. N. A., 118 Hawthorne Pl., Ithaca, N. Y. (abcdefgh)
Clark, Prof. R. H., University of Manitoba, Dept. of Civil Engineering, Winnipeg, Canada (g)
Code, Mr. William E., Colorado A. and M. College, Fort Collins, Colo. (g)
Corton, Mr. Edward L., Jr., 4535 Silver Hill Rd., Washington 20, D. C. (c)
Cotell, Mr. Robert D., South Sea Ave., West Yarmouth, Mass. (abcdefgh)
Council, Mr. Thomas C., 161-09 84th Dr., Jamaica 2, N. Y. (c)
Craig, Mr. Alan Leigh, Everglades Experiment Sta., Bell Glade, Fla. (ceg)
Cude, Mr. William C., Engineer Research and Development Labs., Fort Belvoir, Va. (a)
Davidson, Capt. Carl M., 1019 12th St., N., St. Petersburg, Fla. (g)
Davidson, Mr. David F., U. S. Geological Survey, P. O. Box 1390, Plant City, Fla. (ae)
Davis, Mr. Lee C., Woods Hole Oceanographic Institution, Woods Hole, Mass. (e)
Davis, Mr. Rollin E., 216 N. Big Spring, Midland, Texas (abdh)
Deitch, Mr. Samuel, U. S. Weather Bureau, Atlantic City, N. J. (c)
Delflache, Mr. Andre P., 3810 2nd St., N.W., Calgary, Alta., Canada (bde)

Dervin, Mr. Raymond W., 415 Viking St., North Canton, Ohio (c)
Dhir, Mr. R. D., Central Water and Power Comm., Curzon Rd., Barracks, New Delhi, India (cg)
Dick, Mr. L. Walter, U. S. Weather Bureau, Davenport, Iowa (cg)
Dietrich, Dr. Richard V., P. O. Box 1, Hammond, N. Y. (fh)
Diment, Mr. William H., 1753 Massachusetts Ave., Cambridge 40, Mass. (abdh)
Dortignac, Mr. Edward J., U. S. Forest Service, Waterways Experiment Sta., Vicksburg, Miss. (cg)
Duffield, Capt. Albert V., 2218 Fourth Ave., N., Great Falls, Mont. (c)
Dunn, Dr. James R., Geology Dept., Rennselaer Polytechnic Institute, Troy, N. Y. (f)
Edmonston, Mr. A. D., P. O. Box 1079, Sacramento 5, Calif. (g)
Eichmeier, Mr. Albert H., U. S. Weather Bureau, East Lansing, Mich. (c)
Eisenhuth, Mr. Harold P., U. S. Geological Survey, Denver Federal Center, Denver, Colo. (g)
Ekern, Dr. Paul C., Jr., University of Wisconsin, Madison, Wis. (cg)
El-Wardani, Mr. Sayed Aly, Scripps Institution of Oceanography, La Jolla, Calif. (e)
Enfield, Lt. Bernard M., 485th Engr. C Bn., APO 225, c/o P.M., New York, N. Y. (eg)
Enzmann, Dr. Robert Duncan, Dept. of Geology, O'okiep Copper Co., Ltd., Nababeep, Namaqualand, Cape Prov., South Africa (h)
Evans, Mr. Daniel D., Iowa State College, Ames, Iowa (abcdefgh)
Evenson, Mr. Robert E., 2931 Calderwood Lane, Apt. 40, Sacramento 15, Calif. (fg)
Feo-Codecido, Mr. Gustavo, Mene Grande Oil Co., Apartado 709, Caracas, Venezuela (fg)
Fetzer, Mr. Edwin L., Heiland Exploration Co., Examiner Bldg., Calgary, Alta., Canada (b)
Fitzgerald, Mr. Donald R., 5621 University Ave., Chicago 37, Ill. (cd)
Fluhr, Mr. Thomas W., P. O. Box 431, Downsville, N. Y. (dgh)
Fritz, Mr. Sigmund, U. S. Weather Bureau, Washington 25, D. C. (c)
Frost, Mr. H. H., 525 Mayrant, Dallas 8, Texas (b)
Gaede, Mr. John E., Geophysical Service, Inc., 6000 Lemmon Ave., Dallas, Texas (bdh)
Gane, Dr. P. G., Geophysical Research Inst., Witwatersrand Univ., Johannesburg, South Africa (bd)
Ganeff, Dr. J. M., Dept. of Agrology, I.N.E.A.C., Yangambi, Belgian Congo (g)
Gessel, Dr. Stanley P., College of Forestry, University of Washington, Seattle 5, Wash. (fg)
Getz, Mr. Frank A., 1652 1/2 Morton Ave., Los Angeles 26, Calif. (abcdefgh)
Ghosh, Dr. S. N., Physics Dept., Duke University, Durham, N. C. (abcdefgh)
Gibbons, Dr. John J., 209 W. Foster Ave., State College, Pa. (d)
Gittings, Mr. Homer T., Jr., 1537 B 41st St., Los Alamos, N. Mex. (cdeh)
Goldberg, Dr. Leo, 1308 E. Ann St., Ann Arbor, Mich. (d)
Granbois, Mr. Kenneth J., R. D. No. 2, Conestoga, Pa. (g)
Greene, Mr. John A., Apt. 1E, Bldg. 9, Caroline Terrace Apts., North Augusta, S. C. (cg)
Hadley, Mr. Richard F., U. S. Geological Survey, 503 Federal Bldg., Salt Lake City 1, Utah (eg)
Hanks, Mr. Ronald J., Soils Dept., University of Wisconsin, Madison 6, Wis. (g)
Harbaugh, Mr. John W., 230 Aurora St., Hudson, Ohio (f)
Hardy, Mr. Albert Victor, P. O. Box 5277, State College Sta., Raleigh, N. C. (c)
Hare, Dr. F. Kenneth, Geography Dept., McGill University, Montreal, Canada (ceg)
Harshbarger, Mr. Harold B., 1607 N. Roosevelt St., Falls Church, Va. (c)
Hart, Dr. Samuel A., Div. of Irrigation and Soils, Univ. of California, Los Angeles 24, Calif. (g)
Havens, Dr. Ralph J., Naval Research Laboratory, Washington 20, D. C. (d)
Hayes, Mr. Philip T., U. S. Geological Survey, P. O. Box 829, Carlsbad, N. Mex. (acfh)
Hazelworth, Mr. John B., 428 Wildwood Ave., Jackson, Mich. (bcde)
Heenan, Mr. P. R., 285 8th Ave., Larder Lake, Ont., Canada (abfgh)
Heilborn, Mr. George, 1326 19th St., N.W., Washington 6, D. C. (e)
Hemingway, Mr. Kenneth G., 55th Rec. Tech. Sqdn., APO 845, c/o P.M., New York, N.Y. (abcdefgh)
Heppner, Mr. James P., Geophysical Institute, University of Alaska, College, Alaska (bcdh)
Herzog, Mr. Leonard F., II, 475 Glen Rd., Weston, Mass. (abdh)
Hickenlooper, Mr. Irby J., 1007 W. Western Ave., Urbana, Ill. (g)
Hill, Dr. E. G., British Joint Services Mission, 1910 K St., N.W., Washington 6, D. C. (de)
Hobson, Dr. J. E., Stanford Research Institute, Stanford, Calif. (bd)
Hooton, Mr. John A., 1225 Springdale Rd., N.E., Atlanta, Ga. (abcdefgh)
Howe, Mr. Richard H., 74 Rumford Ave., Mansfield, Mass. (g)
Hubert, Lt. William E., 11-B4 Sheridan Village, Schenectady, N. Y. (bc)
Hughes, Mr. Paul W., P. O. Box 1022, Alpine, Texas (g)
Hume, Mr. James D., Dept. of Geology, University of Michigan, Ann Arbor, Mich. (eg)
Hussey, Mr. Clarence B., P. O. Drawer 2100, Houston, Texas (e)
Ingersoll, Dr. Alfred C., California Institute of Technology, Pasadena 4, Calif. (eg)
Irujo, Mr. Juan Ignacio, Edificio Loira, Ave. La Vega, El Paraiso, Caracas, Venezuela (bceg)
Jackson, Mr. Everett D., U. S. Geological Survey, S. 157 Howard St., Spokane 8, Wash. (f)
Jacobs, Prof. G. B., P. O. Box 142, College, Alaska (d)
Johnson, Mr. Bertrand L., 1414 Highland Dr., Woodside Park, Silver Spring, Md. (abcdefgh)
Johnson, Mr. Byron K., 663 Second St., Orleans Parkway, New Orleans 21, La. (abdh)
Johnson, Mr. David S., Dept. of Meteorology, University of California, Los Angeles 24, Calif. (c)
Jones, Mr. Donald W., Seismograph Dept., Sun Oil Co., Beaumont, Texas (abdfh)

Jones, Mr. M. P., 4717 Willow St., Bellaire, Texas (ab)
Joralemon, Dr. Peter, 1127 Woodside Ave., Park City, Utah (f)
Kabraji, Dr. K. J., Central Engineering Authority, Govt. of Pakistan, Karachi 1, Pakistan (abcdefgh)
Kaciak, Mr. William, 235 W. 19th St., New York 11, N. Y. (cdeg)
Katzin, Mr. Martin, 154 Fleetwood Terrace, Silver Spring, Md. (cde)
Kaupke, Mr. Charles L., 1302 Security Bank Bldg., Fresno, Calif. (cg)
Kehrlein, Mr. Oliver, 71 Jordan Ave., San Francisco, Calif. (g)
Keith, Mr. Hubert C., 5903 Yorkwood Rd., Baltimore 12, Md. (c)
Kenworthy, Mr. Philip W., 8 Grant Ave., Watertown 72, Mass. (c)
Kerley, Prof. James J., Jr., 6203 Forest Rd., Cheverly, Md. (abh)
King, Mr. Jean I., Dept. of Physics, University of Utah, Salt Lake City 1, Utah (c)
Kleinpeter, Mr. Henry E., Jr., R.F.D. 3, Baton Rouge, La. (abdgh)
Kottlowski, Mr. Frank E., New Mexico Bureau of Mines, New Mexico School of Mines, Socorro, N. Mex. (dfh)
Kramer, Mr. Howard S., 2775 73rd Pl., Hyattsville, Md. (e)
Kramp, Major Joseph J., 2268 West Park Ave., Napa, Calif. (a)
Kramsky, Mr. Meyer, 1816 N. Avon St., Burbank, Calif. (g)
Krick, Dr. Irving P., 460 S. Broadway, Denver, Colo. (c)
Kuiper, Dr. Gerard P., Yerkes Observatory, Williams Bay, Wis. (abcdh)
Lacy, Dr. Willard C., Cerro de Pasco Corp., La Oroya, Peru (bdfh)
Landers, Mr. Holbrook, 307 Roosevelt Dr., Tallahassee, Fla. (c)
Lewis, Mr. George J., Jr., Scripps Institution of Oceanography, La Jolla, Calif. (e)
Lewis, Major Thomas H., IV, 11th Wea. Sq., APO 942, c/o Postmaster, Seattle, Wash. (ce)
Libbey, Mr. Donald S., Hot Springs National Park, Hot Springs, Ark. (cg)
Liebrecht, Mr. Lawrence C., 7704 Alpine St., S.E., Washington 19, D. C. (aefg)
Lincoln, Mr. John H., 3404 S.W. 104th St., Seattle 66, Wash. (e)
Long, Mr. James A., United Geophysical Co., Rua Uruguaiona 118, Rio de Janeiro, Brazil (b)
Low, Dr. John H., 98 Rivercrest Rd., Toronto, Ontario, Canada (d)
Lowery, Mr. Thaddieus L., Arnold Eng. Development Center, Tullahoma, Tenn. (cg)
Lyon, Dr. Waldo K., 1330 Alexandria Dr., San Diego 7, Calif. (e)
MacCready, Mr. Paul B., Jr., Aeronautics Dept., California Institute of Technology, Pasadena, Calif. (cg)
Machado, Eng. Frederico, Horta, Faial, Azores Islands (bf)
MacLean, Mr. Duart A., Alderley Rd., R. R. 1, Royal Oak, V. I., B. C., Canada (g)
Magill, Mr. Paul L., Greer Rd., Woodside, Calif. (abcdefgh)
Mallinckrodt, Mr. A. J., 2303 MacFarland Dr., Cocoa, Fla. (d)
Mann, Dr. John A., P. O. Box 1200, Bakersfield, Calif. (bh)
Marks, Mr. Wilbur, Dept. of Meteorology, New York University, Bronx 53, N. Y. (ce)
Maxwell, Mr. Arthur E., P. O. Box 241, Del Mar, Calif. (e)
May, Mr. Paul R., U. S. Geological Survey, P. O. Box 65, Miles City, Mont. (adefgh)
McClain, Mr. E. Paul, Dept. of Meteorology, University of Washington, Seattle 5, Wash. (c)
McFarland, Maj. Archie M., Lab. of Climatology, Johns Hopkins University, Seabrook, N. J. (cg)
McGough, Mr. Raymond J., 5520 Parkland Village, Apt. 201, Washington 19, D. C. (ceg)
McKillop, Mr. Donald H., 5903 Lemon St., Long Beach 5, Calif. (g)
McMillen, Mr. Neil J., 202 Demorest Ave., Columbus 4, Ohio (g)
Merriell, Mr. Frank C., P. O. Box 988, Grand Junction, Colo. (cg)
Meyer, Dr. Charles, P. O. Box 597, Butte, Montana (abdf)
Meyer, Mr. Walter R., 1002 N. 4th St., Garden City, Kans. (g)
Miller, Mr. Carl R., Route 2, Box 87, Arvada, Colo. (g)
Miller, Mr. Martin A., 22 Pierce Rd., Watertown 72, Mass. (c)
Miller, Dr. William A., RCA Laboratories, Rocky Point, L. I., New York (cd)
Moody, Mr. John D., P. O. Box 1290, Fort Worth, Texas (befh)
Moore, Dr. Terris, University of Alaska, College, Alaska (ac)
Moore, Dr. Wayne E., P. O. Box 611, Blacksburg, Va. (eh)
Moreland, Mr. William N., 3874 Eloise St., Jacksonville, Fla. (cg)
Mussetter, Mr. William, Mapping and Charting Research Lab., Ohio State University, Columbus 10, Ohio (a)
Mutch, Mr. A. D., Geological Dept., Falconbridge Nickel Mines, Falconbridge, Ont., Canada (abcdfgh)
Myers, Mr. Henry C., Route 1, Box 120, Palm City, Calif. (g)
Nanda, Dr. Jatinder Nath, 5241 Broad Branch Rd., N.W., Washington 15, D. C. (bcd)
Nazarek, Mr. Alex, Geophysical Research Directorate, Air Force Cambridge Research Center, 230 Albany St., Cambridge 39, Mass. (cd)
Neilson, Dr. James M., 1602 E. Houghton Ave., Houghton, Mich. (h)
Nelson, Mr. Robert L., 50 W. Floral Ave., Arcadia, Calif. (b)
Nelson, Mr. Samuel B., 251 S. Larchmont Blvd., Los Angeles, Calif. (adfgh)
Nigudkar, Mr. Shyam D., 6-B 677 Lodi Road Colony, New Delhi, India (cg)

Norton, Mr. Kenneth A., Radio Division, National Bureau of Standards, Boulder, Colo. (acd)
Novotny, Mr. James R., 220 W. Fairview Blvd., Inglewood, Calif. (d)
Novotny, Mr. Robert T., 241 E. Mosholu Parkway, Bronx 67, N. Y. (abcdefgh)
Nowicki, Mr. Albert L., 6909 Massachusetts Ave., N.W., Washington, D. C. (ag)
Nuttli, Mr. Otto W., Institute of Technology, 3621 Olive St., St. Louis 8, Mo. (ab)
O'Dea, Mr. Patrick L., 1830 K St., N.W., Washington 6, D. C. (d)
Odom, Mr. Leo M., P. O. Box 267, Baton Rouge, La. (cg)
O'Donnell, Brother G. A., 33 Beechmont Dr., New Rochelle, N. Y. (d)
Ohmstede, Mr. William D., 11628 Montana Ave., Los Angeles 49, Calif. (ce)
Opland, Mr. Homer N., 1424 Rhode Island Ave., N.W., Washington 5, D. C. (bg)
Orr, Mr. James B., 1717 Rossmont Dr., Redlands, Calif. (f)
Ortman, Mr. Paul Henry, 807 Hyperion Ave., Apt. 32, Los Angeles 29, Calif. (eg)
Osborn, Lt. Col. Robert R., USAF, 316 Glen Park Ct., Bridgeton, N. J. (c)
Pack, Mr. Donald H., P. O. Box 2080, Anchorage, Alaska (abcd)
Page, Dr. R. M., 5400 Branch Ave., Washington 20, D. C. (c)
Paranathala, Mr. W. E., Central Designs and Research Div., Jawatta Rd., Colombo 5, Ceylon (acegh)
Pastir, Mr. Dominic S., 1007 Michigan Ave., Fresno, Calif. (g)
Patton, Mr. Clyde P., 2214-B Sacramento St., Berkeley 2, Calif. (c)
Pattullo, Miss June G., 2227 Felspar St., San Diego 9, Calif. (ce)
Pesce, Mr. Gabriel V., 107a Lincoln Hall, Cornell University, Ithaca, N. Y. (cg)
Pettit, Miss Helen B., 963 E. Villa St., Pasadena 4, Calif. (cd)
Plaster, Mr. Roger G., 6425 Cross Ave., Jacksonville 8, Fla. (c)
Porro, Mr. Emo D., 208 Robin Way, Palo Alto, Calif. (f)
Powers, Mr. Charles F., Dept. of Conservation, Cornell University, Ithaca, N. Y. (e)
Price, Dr. Peter, 143 3rd St., Noranda, Quebec, Canada (abdfh)
Rampy, Mr. Stanley W., 641 S. Rotherwood St., Evansville 14, Ind. (cg)
Reeves, Mr. Robert G., Route 2, Box 313, Reno, Nev. (df)
Remson, Mr. Irwin, 308 Mead Ave., Bridgeton, N. J. (g)
Riccio, Mr. Joseph F., Tropical Oil Co., Apartado Aereo No. 3533, Bogota, Colombia (abdegh)
Richards, Mr. Adrian F., 7768 Herschel Ave., La Jolla, Calif. (de)
Richards, Dr. Francis A. Richards, Woods Hole Oceanographic Institution, Woods Hole, Mass. (e)
Richardson, Mr. Raymond M., U. S. Geological Survey, 2-C P.O. Bldg., Knoxville, Tenn. (dg)
Richmond, Mr. Gerald M., U. S. Geological Survey, Denver Federal Center, Denver, Colo. (acdgh)
Robinson, Mrs. Margaret K., 7721 Hillside Dr., La Jolla, Calif. (e)
Rogers, Mr. Thomas F., 44 Kendall Park, Waltham, Mass. (bcdgh)
Rolfe, Mr. Bernard N., 118 S. Barnard St., State College, Pa. (g)
Ross, Mr. Ralph B., 2401 Collins Rd., Pittsburgh 35, Pa. (b)
Roth, Mr. Herman P., 211 Anderson St., Manhattan Beach, Calif. (c)
Roth, Mr. R. J., Crop-Hail Actuarial Assn., 209 W. Jackson Blvd., Chicago 6, Ill. (c)
Roth, Dr. Robert S., University of Illinois, 121 Natural Resources Bldg., Urbana, Ill. (f)
Roy, Dr. Sharat K., Chicago Natural History Museum, Chicago 5, Ill. (f)
Rush, Mr. Richard W., 924 Lansing Ave., Austin, Minn. (e)
Russell, Mr. Robert H., Div. of Water Resources, 406 Transportation Bldg., Olympia, Wash. (g)
Sanders, Mr. William L., 2226 N. Rosemead Blvd., El Monte, Calif. (abfh)
Sargent, Mr. Donald M., 615 8th Ave., W., Calgary, Alta., Canada (b)
Sartain, Mr. Raymond R., P. O. Drawer 2100, Houston, Texas (e)
Schaffel, Mr. Simon, Dept. of Geology, City College of New York, 137th St. and Convent Ave., New York 31, N. Y. (fh)
Schneible, Mr. Douglas E., Hydraulics Branch, Bureau of Public Roads, Washington 25, D. C. (g)
Schroeder, Mr. Kenneth B., 581 S. High St., Denver, Colo. (g)
Schwarck A., Sr. Armando, Dirección de geologia, Ministerio de Minas e Hidrocarburos, Veroes a Santa Capilla, Caracas, Venezuela (bgh)
Sclar, Dr. Charles B., Battelle Memorial Institute, 505 King Ave., Columbus 11, Ohio (abefh)
Scott, Mr. James Stuart, 540 Murdock Ave., Noranda, Que., Canada (d)
Scruton, Mr. Philip C., 632 Diamond St., San Diego 9, Calif. (abefgh)
Seiden, Mr. Hyman, 829 1/3 N. Formosa Ave., Los Angeles 46, Calif. (h)
Shjeflo, Mr. Jelmer B., P. O. Box 90, Dickinson, N. Dak. (g)
Silver, Mr. Caswell, 1800 Ridgecrest Dr., Albuquerque, N. Mex. (defgh)
Singer, Mr. Irving A., 136-55A 68 Dr., Kew Garden Hills, Flushing, N. Y. (bcdeg)
Smith, Prof. Dudley T., 523 7th Ave., Watervliet, N. Y. (bh)
Smith, Mr. Markwick K., Jr., 90 Westgate, Cambridge 39, Mass. (abd)
Sniegocki, Mr. Richard Ted, P. O. Box 115, Fullerton, Nebr. (abdgh)
Southwick, Mr. Peter F., 256 Westgate West, Cambridge 39, Mass. (bde)
Sprinkel, Mr. Robert L., Jr., 2080 Obispo Ave., Long Beach 4, Calif. (gh)
Stapleton, Prof. Herbert N., University of Massachusetts, Amherst, Mass. (cg)
Stelson, Mr. Thomas Eugene, P. O. Box 341, Carnegie Institute of Technology, Pittsburgh 13, Pa.(g)
Steppan, Mr. Herbert J., Rosa Duarte 19, Trujillo City, Dominican Republic (cg)

Still, Mr. Arthur R., P. O Box 1512, Prescott, Ariz. (abdfh)
Stolzy, Mr. Lewis H., 910 C Walnut Lane, East Lansing, Mich. (cg)
Storey, Mr. Theodore G., P. O. Box 245, Berkeley 1, Calif. (cg)
Stowell, Mr. David J., P. O. Box 19, Fairbanks, Alaska (c)
Stratton, Dr. E. F., 3706 Turnberry Circle, Houston 5, Texas (bfh)
Sutton, Mr. Robert G., P. O. Box 1026, Alfred, N. Y. (abdefh)
Terry, Mr. Richard D., 4606 Denker Ave., Los Angeles 62, Calif. (efg)
Thatcher, Dr. Everett W., 2661 Poinsettia Dr., San Diego 6, Calif. (bcdeh)
Thiel, Mr. Edward, Dept. of Geology, University of Wisconsin, Madison, Wis. (abeg)
Thompson, Mr. F. L., 1140 40th St., Sacramento 16, Calif. (cg)
Travis, Mr. Fred L., Jr., 536 Milton Ave., Casper, Wyo. (abdh)
Underhill, Mr. A. G., 11439 75th Ave., Edmonton, Alta., Canada (g)
Van Atta, Dr. L. C., Hughes Aircraft Co., Culver City, Calif. (d)
Van Dorn, Mr. Wm. G., 310 Playa Del Norte, La Jolla, Calif. (e)
Vanni, Mr. Vincent, 318 S. Pasfield St., Springfield, Ill. (eg)
Voelker, Dr. Charles H., 200 N. Front St., Chestertown, Md. (ceg)
Volkmann, Mr. G. H., Woods Hole Oceanographic Institution, Woods Hole, Mass. (e)
Vollenweider, Mr. H., c/o Shell C.P.C., Caracas, Venezuela (acdefg)
Waldron, Mr. John F., 1011 McKendrie St., San Jose, Calif. (g)
Ward, Mr. James B., Knappen-Tippett-Abbett Eng. Co., Box 42, Athens, Greece (bcfh)
Warn, Prof. G. Frederick, Dept. of Geology, Texas Technical College, Lubbock, Texas (abcdefgh)
Warner, Mr. Roy F., 1872 N. Howard St., St. Paul 9, Minn. (g)
Waterman, Mr. Willis D., 227 S. Penn Ave., Salina, Kans. (g)
Watts, Mr. George M., 521 Monticello Dr., Falls Church, Va. (eg)
Weis, Mr. Leonard W., Dept. of Geology and Mineralogy, Pillsbury Hall, University of Minnesota, Minneapolis 14, Minn. (abcdefgh)
Weitz, Prof. John H., R. D. 3, Bethlehem, Pa. (fh)
White, Mr. Robert M., Geophysical Research Directorate, Air Force Cambridge Research Center, 230 Albany St., Cambridge 39, Mass. (ceg)
Whitmore, Dr. D. R. E., P. O. Box 1340, Prince Rupert, B.C., Canada (h)
Wickremesinghe, Mr. Tissa, 8 Alfred House Rd., Colombo 3, Ceylon (aceg)
Wilcox, Mr. John B., Washington Grove, Md. (d)
Williams, Mr. John R., U. S. Geological Survey, A-32 Washington Auditorium, Washington 25, D. C. (g)
Winkler, Mr. Hartmut A., Campus Sta., Socorro, N. Mex. (b)
Winslow, Mr. John D., U. S. Geological Survey, 52 S. Starling St., Columbus 8, Ohio (bdgh)
Wood, Mr. Perry R., 2520 Marconi Ave., Sacramento 15, Calif. (g)
Wood, Mr. Robert H., 924 Moissan St., Arvida, Que., Canada (cg)
Woodard, Mr. H. H., Rings Island, Newburyport, Mass. (fh)
Woodruff, Mr. Neil P., Soil Conservation Service, c/o Agronomy Dept., Kansas State College, Manhattan, Kans. (cg)
Worthington, Mr. L. Valentine, P. O. Box 368, Woods Hole, Mass. (e)
Wozab, Mr. David H., 4916 Brompton Ave., Bell, Calif. (eg)
Yost, Mr. Coyd B., Jr., 2246 W. Devonshire Ave., Phoenix, Ariz. (dfgh)
Young, Mr. Gordon A., Mene Grande Oil Co., Apartado 709, Caracas, Venezuela (eh)
Yu, Dr. Yi-Yuan, Dept. of Applied Mechanics, Washington University, St. Louis, Mo. (egh)
Ziegler, Mr. James K., 614 25th Ave., N.W., Calgary, Alta., Canada (b)
Zunino, Sr. Juan J., Humberto Primo 3486, Buenos Aires, Argentina (abdh)

Transferred from Inactive to Active Status

Capello, Mr. James J., 407 Essex Ave., Chevy Chase 15, Md. (d)
Guerrini, Mr. Vincent, "Corlan" Castletroy, Limerick, Eire (cd)
Hafstad, Mrs. Katharine C., Operations Research Office, Johns Hopkins University, 6410 Connecticut Ave., Chevy Chase, Md. (cdg)
Irwin, Mr. Raymond L., Washington District, Corps of Engineers, 1st and Douglas Sts., N.W., Washington 2, D. C. (cg)

Thirty-Third Annual Meeting, Washington, D. C., May 5-7, 1952--As announced in the August issue of the Transactions, the Thirty-Third Annual Meeting will be held in Washington, D. C., May 5-7, 1952 (Monday to Wednesday). Plans for the meeting are under way, and it is anticipated that all Sections will have sessions, as well as the Union as a whole. Place this meeting on your calendar and make plans to come.

This announcement serves also as an invitation for members and others to send word of plans for papers to be presented. Titles of papers with three copies of the abstract should be sent as soon as possible, and not later than March 10, 1952, with advice concerning the time required (most papers are allowed from ten to twenty minutes) and the projection equipment needed. Send this word to the office of AGU at 1530 P Street, N.W., Washington 5, D. C., or to the Secretary of the appropriate Section, as follows:

Geodesy	Frank L. Culley	U. S. Coast and Geodetic Survey Washington 25, D. C.
Seismology	James T. Wilson	Department of Geology University of Michigan Ann Arbor, Michigan
Meteorology	Woodrow C. Jacobs	4302 Kentbury Drive Bethesda 14, Md.
Terrestrial Magnetism and Electricity	L. R. Alldredge	3133 Jennings Road Kensington, Md.
Oceanography	Richard H. Fleming	Department of Oceanography University of Washington Seattle 5, Washington
Volcanology	Felix Chayes	Geophysical Laboratory 2801 Upton Street, N.W. Washington 8, D. C.
Hydrology	Ray K. Linsley or Ralph N. Wilson (Program Chairman)	Dept. of Civil Engineering Stanford University Stanford, California 3900 Hamilton St., Apt. E-101 Hyattsville, Maryland
Tectonophysics	Wilbur S. Burbank	3346 Runnymede Place, N.W. Washington 15, D. C.

As the Section Secretaries reserve the right to close filled programs in advance of the date indicated, it is desirable that word concerning papers be sent in early.

Complete manuscripts of papers should be forwarded in triplicate by April 15, 1952 in order that news releases may be prepared. Indicate whether the paper is being submitted for the program only or also for consideration for publication in the Transactions. (Papers for publication only are also welcome for consideration for the Transactions.)

If a paper is written in collaboration, please indicate by whom it will be presented. Arrangements can usually be made for presentation of papers by authors who are unable to attend.

The Chairman of the Committee on Meetings (J. P. Marble, 321 U. S. National Museum, Washington 25, D. C.) invites suggestions and comments that will be helpful in planning this meeting. Especially invited are comments relating to papers and symposia bearing on more than one Section.

Make hotel or room reservations directly with the hotel of your choice at an early date. Failing on the first attempt, bear in mind that advance bookings not taken up are cancelled two weeks in advance, so a follow-up request in mid-April may bring the desired response. It is anticipated that we will make block booking at two or three hotels again, an announcement concerning which will appear in the Special Announcements of the February 1952 issue of the Transactions.

John Putnam Marble, Chairman
Committee on Meetings

Twenty-Seventh Regional Meeting--The Twenty-Seventh Regional Meeting will be held at California Institute of Technology in Pasadena, California, February 8-9, 1952. J. W. Johnson of Berkley is Chairman of the Regional Committee and Vito A. Vanoni of Pasadena is making local arrangements.

GEOPHYSICAL RESEARCH CORPORATION

Geophysical Prospecting
Application of Geophysical Methods in the Petroleum Industry

2607 North Boston Place
Tulsa 6, Oklahoma

GULF RESEARCH & DEVELOPMENT COMPANY
GULF OIL CORPORATION

Geophysical and Other Research
Relating to the Petroleum Industry

P. O. Drawer 2038
Pittsburgh 30, Pennsylvania

INSTITUTE OF GEOPHYSICS

UNIVERSITY OF CALIFORNIA

Los Angeles 24, California

RANNEY METHOD WATER SUPPLIES, INC.

Ground Water Exploration and Development

841 Alton Avenue
Columbus 3, Ohio

RUSKA INSTRUMENT CORPORATION

Developers, Designers, and Manufacturers of Instruments for Field and Observatory Use
Magnetic, Geodetic, Seismic, and Meteorological Work

4607 Montrose Boulevard
Houston 6, Texas

SEISMOGRAPH SERVICE CORPORATION

Seismic Exploration Service for
Oil and Gas Structures throughout the World

P. O. Box 1590
Kennedy Building
Tulsa 1, Oklahoma

SPRENGNETHER INSTRUMENT COMPANY

Manufacturer of Seismological and Geophysical Instruments
Instrumental Development and Research

4567 Swan Avenue
St. Louis 10, Missouri

TRANSACTIONS
AMERICAN GEOPHYSICAL UNION

Volume 32 DECEMBER 1951 Number 6

A DISCUSSION OF THE ACCURACY REQUIRED IN ASTRONOMIC DETERMINATIONS FOR LAPLACE AZIMUTH CONTROL

Warren D. Forrester

Abstract--The need of increasing the number of observations for azimuth as one approaches higher latitudes is discussed and frequent reference is made to differences of opinion existing between two members of the Geographical Service of Norway in regard to the value of Laplace azimuths in the adjustment of triangulation observed in the Far North. A tabulation of the ratio of work required at any latitude, relative to that at 45° latitude, is given for both azimuth and longitude observations in order to secure comparable accuracy.

As precise triangulation and shoran triangulation in Canada began to reach latitudes north of 60°, the question of how difficulties in observing astronomic azimuths and longitudes at high latitudes would affect the Laplace adjustment of triangulation nets became of great interest to the Geodetic Survey of Canada. Investigation into this matter turned up a series of controversial articles in the Bulletin Géodesique by J. SCHIVE [1934, 1935, 1936], HANS JELSTRUP [1934], and GUNNAR JELSTRUP [1936], all of the Geographical Service of Norway.

Schive maintains that for the purpose of Laplace adjustment it is necessary to prevent the errors in astronomic longitude and azimuth from increasing as operations proceed northwards, if the accuracy of the adjustment is not to suffer. On the other hand, the Jelstrups claim that since geodetic azimuths calculated through triangulation nets also become less accurate as the latitude increases, nothing is to be gained by maintaining the accuracy of the astronomic measurements.

The principle behind Laplace adjustment--In an attempt to clear up this controversy, let us examine the method in which the Laplace adjustment is used to control a triangulation net. Imagine that we run a net from the point P_1 on the surface of the Earth to the point P_2 (see Fig. 1). The solid lines represent the true positions of the lines of the end figure of the net, and P_2 is the actual position of the end point. The dotted lines represent the position that we calculate the lines of the end figure to have on the basis of our triangulation measurements from the point P_1, and P_2' represents the calculated position of the end point. Experience has shown that the calculated position of the net tends to twist away from the true position by an appreciable amount. Obviously, the tendency to twist out of position is in no way dependent upon the latitude of the operation, since the errors that cause the twisting are merely errors in the measurements of the horizontal angles and the base lines in the network.

If we can now obtain some direct measurement of the amount that the net has twisted, we can apply an adjustment to bring it back by the same amount, and thus obtain calculated positions for the points in the net which are much closer to the true positions. With this purpose in mind, let us again consider Figure 1. P_2K and $P_2'K'$ represent the true and calculated positions of the last line in the net, and r is the angle made at the intersection of these two lines produced. The angle r is dependent for its size solely upon the amount that the calculated net has twisted, and hence forms an ideal measurement of the amount of twist to correct for in the adjustment. The problem becomes, then, how does our ability to assess the angle r depend upon the latitude.

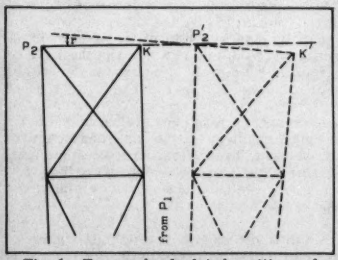


Fig. 1--True and calculated positions of end of triangulation network

The Laplace equation--Before introducing the Laplace equation, we should point out that the geographic position of a point may be determined by two methods; namely, by astronomic means, and by continuous triangulation from a fixed datum. If the Earth were a homogeneous mass, the direction of gravity would be coincident with the normal to the spheroid of reference, and the values obtained by these two methods would be in agreement. However,

the lack of homogeneity in the Earth's mass gives gravity a direction not coincident with the normal to the spheroid, and hence the position determined astronomically differs from that obtained through triangulation. Were it not for this lack of homogeneity, geodetic triangulation would not be necessary. The Laplace equation is a relation between astronomic and geodetic coordinates and azimuths. It states that at a point on the surface of the Earth having astronomic longitude = λ_a, geodetic longitude = λ_g, and latitude = ϕ, the geodetic azimuth, α_g, of a line will bear the following relation to the astronomic azimuth, α_a, of the same line: $\alpha_g = \alpha_a + (\lambda_a - \lambda_g) \sin \phi$.

To make use of this equation, we measure, at the point P_2, the astronomic azimuth, α_a, of the line P_2K, and the astronomic longitude, λ_a. Our calculations through the triangulation give us the following geodetic values at the end point of the net: geodetic longitude = λ_g' and geodetic azimuth of $P_2'K' = \alpha_g'$. These values are not, however, the true geodetic values at the actual end point P_2, but are the values at the erroneous end point, which we have called P_2'.

We do not know the true geodetic values at the point P_2 as yet, but we may give them the following symbols: geodetic longitude = λ_g and geodetic azimuth of $P_2K = \alpha_g$.

When we calculate our Laplace azimuth, which we shall call α_L, we get $\alpha_L = \alpha_a + (\lambda_a - \lambda_g') \sin \phi$. Since we should have used λ_g in place of λ_g' in this equation, our value for α_L will differ from the true geodetic azimuth, α_g, of line P_2K by the quantity $(\lambda_g - \lambda_g') \sin \phi$, provided that our astronomic values of α_a and λ_a are errorless. Therefore, we may say

$$\alpha_L = \alpha_g + (\lambda_g - \lambda_g') \sin \phi \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

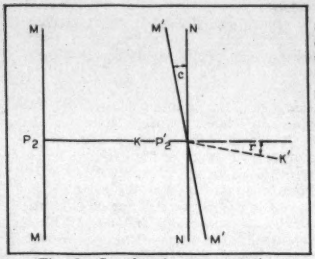


Fig. 2--Graphical representation of azimuth closure

In Figure 2, MM is the meridian passing through P_2, and M'M' is the meridian passing through P_2'. Because of the convergence of the meridians, M'M' is not parallel to MM. NN, however, has been drawn through the point P_2' parallel to MM. We shall call the amount of convergence c. Hence, angle $NP_2'M' = c = (\lambda_g - \lambda_g') \sin \phi$, which is the expression for convergence of the meridians.

We now see that the value α_g' for the geodetic azimuth of the last line of the net, obtained from our first calculation differs from the true geodetic azimuth, α_g, by the angle $r + c = r + (\lambda_g - \lambda_g') \sin \phi$. Therefore

$$\alpha_g' = \alpha_g + r + (\lambda_g - \lambda_g') \sin \phi \quad \ldots\ldots\ldots (2)$$

The expression for the Laplace residual is the difference between the calculated geodetic azimuth and the azimuth given by the Laplace equation, which, by virtue of (1) and (2), may be written

$$\alpha_g' - \alpha_L = (\alpha_g + c + r) - (\alpha_g + c) = r \quad \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

remembering that $c = (\lambda_g - \lambda_g') \sin \phi$. Thus we see that the expression for convergence of the meridians cancels out of the expression for the Laplace residual, to give the value of r equally accurately for any latitude, provided that our astronomically determined functions be errorless. It is important to again note here that our aim was not to force the line P_2K to adopt the Laplace azimuth, α_L, which would be in error by c, the convergence, but merely to determine the angle r, to use as a measure of the amount of twist adjustment necessary.

Effects of astronomic errors on Laplace residual--So far, we have been assuming that our astronomical observations were errorless. Unfortunately, such is never the case, and we must realize that any error introduced into the Laplace azimuth, α_L, through inaccuracies in the astronomic quantities will appear as a direct error in the value of the Laplace residual, r. Thus, to maintain the accuracy of Laplace adjustment at high latitudes, we must observe astronomic azimuth and longitude to an accuracy at least equal to that at low latitudes.

If we now consider the error in astronomic azimuth to be $d\alpha$, and the error in astronomic longitude to be $d\lambda$, then the resulting error in the Laplace residual will be $d\alpha + d\lambda \sin \phi$ ..... (4) From this expression we see that a given error in astronomic azimuth introduces an equal error

into the Laplace residual for all latitudes, while an error in the astronomic longitude introduces an error proportional to the sine of the latitude.

How the astronomic errors increase with latitude--The treatment used here is similar to that presented by J. SCHIVE [1934], with the exception that we have added a consideration of the error introduced by inaccuracies in the striding levels on the instruments.

(1) Errors in astronomic azimuth--For azimuth, pointings are made on the pole star at an altitude approximately equal to ϕ, the latitude. Thus, an error, p, in pointing on the star at approximate altitude ϕ, introduces an error of p sec ϕ when projected into the horizontal plane of the azimuth.

Similarly, if an error, s, is made in reading the striding level of the instrument in making an azimuth determination at altitude ϕ, the error introduced in the horizontal plane is s tan ϕ.

The error resulting from these two errors is the square root of the sum of the squares of the individual errors, thus

$$\sqrt{p^2 \sec^2 \phi + s^2 \tan^2 \phi} \quad \ldots\ldots (5)$$

To simplify this expression, we may make a slight approximation. Assuming that we are using fairly sensitive level bubbles, to add s^2 under the root sign would not change the expression greatly where ϕ is fairly large. For example, let $\phi = 70°$, p = 2″, and s = 1″ (reasonable pointing and level errors). Substituting in (5) gives us an error of 6″.46.

If we add s^2 under the root sign of (5), we get

$$\sqrt{p^2 \sec^2 \phi + s^2 (1 + \tan^2 \phi)} = \sqrt{(p^2 + s^2) \sec^2 \phi} \quad \ldots\ldots (6)$$

Substituting the above values in (6) gives the value of the error to be 6″.54. Thus, we may assume that our approximation holds quite well at high latitudes, and the error in azimuth may be stated as

$$K \sec \phi \quad \ldots\ldots (7)$$

where $K^2 = p^2 + s^2$, a constant for a particular combination of observer and instrument.

Since the error in azimuth enters directly into (4), the Laplace residual, the ratio of error introduced at latitude ϕ to that introduced at latitude 45° for the same number of observations would be

$$\sec \phi / \sec 45° \quad \ldots\ldots (8)$$

and the ratio by which the amount of work done at latitude ϕ would have to be increased to reduce the azimuth error to the same as at latitude 45° would be

$$\sec^2 \phi / \sec^2 45° \quad \ldots\ldots (9)$$

(2) Errors in astronomic longitude--In longitude determinations, observations are made on stars fairly evenly distributed about the zenith; hence the average of the errors introduced through inaccuracy in star pointing is equal to the time it takes a zenith star to traverse the distance of the pointing error. If the pointing error be p_1, then the error introduced into the longitude will be $p_1 \sec \phi$.

If an error, s_1, be made in reading the striding level on the longitude instrument, it introduces an error of $s_1 \sec \phi$ into the longitude, since it takes a zenith star $s_1 \sec \phi$ to cross the distance of the level error.

The error in the longitude caused by the combination of the pointing and level errors will be

$$\sqrt{(p_1^2 + s_1^2) \sec^2 \phi} = K_1 \sec \phi \quad \ldots\ldots (10)$$

where $K_1^2 = p_1^2 + s_1^2$, a constant for a particular combination of instrument and observer.

Since the error introduced in longitude is multiplied by sin ϕ, as shown in (4), the error in the Laplace residual becomes

$$K_1 \sec \phi \sin \phi = K_1 \tan \phi \quad \ldots\ldots (11)$$

Thus, the ratio of error introduced at latitude ϕ to that introduced at latitude 45° for the same number of observations would be

$$\tan \phi / \tan 45° \quad \ldots\ldots (12)$$

and the ratio by which the amount of work done at latitude ϕ would have to be increased to reduce the error to the same as that at latitude 45° would be

$$\tan^2 \phi / \tan^2 45° \quad \ldots\ldots (13)$$

Tabulation of effect of astronomic errors on Laplace residual--In Table 1 the values of (8), (9), (12), and (13) are shown for various latitudes. The third and fifth columns indicate clearly how we must increase the number of observations for azimuth and longitude as we move northwards. We also see from the table that the effect of the longitude error on the Laplace residual increases with latitude much faster even than the effect of the azimuth error.

It is hoped that this discussion has stressed the need to maintain the accuracy of Laplace astronomic observations in northern latitudes. We have shown here how the amount of work must be increased to maintain this accuracy, but the subject has not been thoroughly dealt with until we mention the practical difficulties met in trying to increase observations in the Far North, where the total field season may be as short as six weeks, and where the daily period of darkness shrinks to one or two hours per night or less. Add to these difficulties the unpleasant and unpredictable

Table 1--Relative error at various latitudes

Latitude	Azimuth		Longitude	
	Ratio of error to that at 45°	Ratio of work required to that at 45°	Ratio of error to that at 45°	Ratio of work required to that at 45°
°				
45	1.00	1.00	1.00	1.00
50	1.10	1.21	1.19	1.42
55	1.23	1.52	1.43	2.04
60	1.41	2.00	1.73	3.00
62	1.51	2.27	1.88	3.54
64	1.61	2.60	2.05	4.20
66	1.74	3.02	2.25	5.04
68	1.89	3.56	2.48	6.13
70	2.07	4.27	2.75	7.55
75	2.73	7.46	3.73	13.93
80	4.07	16.56	5.67	32.16

weather conditions, and it becomes evident that we may sometimes be forced to accept slightly greater errors in Laplace adjustment, where it is not feasible to increase observations sufficiently to compensate for our northerly latitude.

References

JELSTRUP, GUNNAR, L'équation de Laplace aux "hautes latitudes," Bull. Géod., no. 50, pp. 161-166, 1936.

JELSTRUP, HANS, Quelques remarques sur le problème des "hautes latitudes," Bull. Géod. no. 44, pp. 274-279, 1934.

SCHIVE, J., The accuracy's dependence on the latitude in astronomically determined stations, Bull. Géod., no. 42, pp. 80-86, 1934.

SCHIVE, J., Laplace azimuths on high latitudes, Bull. Géod., no. 48, pp. 432-434, 1935.

SCHIVE, J., The Laplace equation, Bull. Géod., no. 52, pp. 493-496, 1936.

Geodetic Survey of Canada,
15 Woodlawn Ave.,
Ottawa, Ontario, Canada

(Manuscript received March 8, 1951; presented at the Thirty-Second Annual Meeting, Washington, D. C., May 2, 1951; open for formal discussion until May 1, 1952.)

Transactions, American Geophysical Union Volume 32, Number 6 December 1951

NEW DETERMINATIONS OF THE VELOCITY OF RADIO WAVES

Carl I. Aslakson

Abstract--The author deduces a new value (299,794.2 ± 1.4 km/sec) for the velocity of propagation of radio waves in a vacuum, as compared to the value of 299,792.4 ± 2.4 km/sec which he had previously reported. Whereas both values were determined by comparison of shoran and geodetic measurements of distances between widely separated points, the new value results from comparisons with improved shoran equipment. The improvements are discussed, with emphasis on the introduction of a gain-riding technique to reduce signal intensities to a constant level and eliminate the possible uncertainties in the signal-intensity corrections which were applied in the earlier determination. The methods of making shoran measurements are outlined and the results of a least-square adjustment of the new shoran data are discussed. In view of the corroborative evidence from other recent determinations, the author recommends abandonment of the Birge statistical value of the velocity of light and states that a value of 299,793 km/sec has been adopted for current shoran measurements.

In 1949 the writer [ASLAKSON, 1949] reported evidence that the BIRGE [1942] statistical value of the velocity of light was too low. That evidence was obtained from a comparison of conventional triangulation with shoran distances. The value derived was 299,792.4 ± 2.4 km/sec. One unsatisfactory feature of this earlier work was the necessity of applying an emperical signal-intensity correction. Although the writer had considerable confidence in the validity of the correction, it was noted that when the signal intensity was ignored, a velocity very close to the Birge value resulted. Since that time great efforts have been made to remove that source of error and those efforts have met with considerable success.

In February and March 1950, the United States Air Force completed an extensive project in Florida, wherein modified shoran equipment was tested. The shoran modifications and improvements were:

(1) Improvement of the goniometer or phase shifters
(2) Improvement of the zeroing of circuits
(3) Addition of a 0.2-mi sweep to permit more accurate pip alignment
(4) Photographic recording of the 0.2-mi oscilloscope, enabling pip alignment errors to be corrected
(5) Adoption of a "gain-riding" equipment to permit manual control of the gains, both in the airborne equipment and at the ground station

The last-named improvement was by far the most important one and it effectively removed the troublesome signal-intensity correction. On the bench, this gain control reduced the shoran readings to the same level over ranges far greater than are ever encountered on shoran missions. In the air an extra operator controlled the gains at all times during the line-crossing procedure. The ground-station operators likewise maintained the gain at a constant level. During rapid fluctuations of the signals considerable operator skill is required to "ride the gains," but nevertheless the effectiveness of the technique was reflected not only in the more uniform "sum-distance" curves but in the final computed results. These improvements will be discussed farther on in this report in greater detail.

Shoran method of distance measurement--For the benefit of those who are unfamiliar with the shoran methods as developed in the United States Air Force under the direction of the writer, the following description of the "line-flying" procedure is presented. The shoran instrument is well known and its technical description will not be included here. Basically, shoran is a system in which the travel time of a pulse from an airborne transmitter to a ground transponder and back is measured in the aircraft by means of a goniometer or phase-advancing system. The frequency is controlled by temperature-controlled crystals at the ground stations. The frequency of the crystal now being used is 93,109.87 cycles/sec, and is chosen because its 537th, 1074th, and 1611th harmonics are 5×10^7, 10×10^7, and 15×10^7 respectively, facilitating comparison with the standard frequencies of WWV. The principle of the shoran design is satisfied for distance when the timing frequency in cycles/sec is equal to one-half the velocity in mi/sec or

$$f_t = V_t/2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where f_t = the frequency of the timing crystal and V_t = the velocity of the impulse in mi/sec.

The velocity of propagation in air at a given instant is given by

$$V = cK_1^{-1/2} = c/\mu \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where V is the velocity of propagation in air, c is the velocity in a vacuum, K_1 is the dielectric constant of the air, and μ is the index of refraction. The values of K_1 and μ are dependent on experimental data and will be discussed later in this paper. The Birge statistical value of c = 299,776 km/sec corresponds to 186,271.8 mi/sec in units in the United States. The correct crystal frequency corresponding to the Birge velocity would have been 186,271.8/2 or 93,135.9. Therefore, it is necessary to apply a correction for the difference between these two frequencies or

$$\Delta T = (93{,}135.9 - 93{,}109.87)/93{,}109.87$$

where ΔT is the ratio by which the distances in miles were increased in the goniometer design to give the correct distance according to the Birge velocity. The timing-crystal frequency is not to be confused with the transmission frequencies. In shoran the airborne transmitter is usually on a frequency of about 220 to 240 mc while the ground stations reply on a common frequency of about 300 mc.

Method of distance measurement--In the geodetic application the distances between shoran ground stations were determined in the following manner: The minimum distance between two stations was obtained by flying across the line between the stations. The counter readings, giving the distances to each ground station were photographically recorded at two-second intervals. The two ground stations involved in a particular line crossing are designated as "rate" and "drift" in accordance with the usual shoran terminology. The minimum sum distance was then determined analytically from a large number of simultaneous observations on each of the two distances, 30 to 40 sum distances being used in each computation. At least 12 and frequently 16 to 18 such measurements were made on each line. Each shoran distance was then corrected by a timing correction and a velocity correction.

The two corrected minimum shoran distances were next reduced to the geodetic distances by geometric corrections involving the altitude of the shoran aircraft and the altitude of the ground stations. The final result was the geodetic distance between stations which was then compared with the geodetic distance as determined by conventional triangulation.

The details of the correction system have been discussed in numerous papers [ASLAKSON and RICE, 1946; ASLAKSON, 1949; ASLAKSON and FICKEISSEN, 1950; ASLAKSON, 1951]. They have been proven in practice and will not be repeated here. However, inasmuch as certain physical measurements are involved in the velocity correction, it is desirable to mention that correction briefly.

The velocity correction--As the shoran ray travels between airplane and ground station it passes through an atmosphere of varying barometric pressure, temperature, and water-vapor pressure. The index of refraction changes continuously along the path, with consequent variations in the velocity of the ray. For this reason it is necessary to correct the measured distance for these changes in velocity from the standard velocity incorporated in the design by the timing-crystal frequency.

The changing index of refraction has a twofold effect on the measured distance: (a) a length change due to the different degrees of bending, and (b) a change in velocity along the path which is a function of the index of refraction in accordance with Eq. (2). In shoran work the lapse rates of barometric pressure, temperature, and water-vapor pressure are observed along the approximate ray path by a second airplane and the data are available for determining the correction. KROLL [1949] has shown that it is possible to combine both effects in a single velocity correction by integrating the basic differential equation of terrestrial refraction along the ray path. However, in shoran work a more practical and far less laborious method has been used and comparisons with the Kroll method show that the differences are generally insignificant. In shoran work the effect of the ray bending is separated from the velocity change by assuming a curved path and combining the bending effect with the geometrical correction. The effect due to change of velocity along the path can then easily be shown to be represented by the relationship

$$\Delta S = \int_0^S \Delta\mu \, ds$$

where ΔS is the velocity correction, $\Delta\mu$ is the index of refraction minus unity, computed at appropriate intervals along the ray path, and ds is the corresponding distance increment computed at appropriate intervals along the ray path. In practice the above expression is evaluated by numerical integration. It is combined with the frequency correction in a single expression of the form

$$\text{Velocity correction in miles} = \left\{ [(V_0 - f)/f] 10^6 - \sum_{h=k}^{h=H} \Delta\mu \right\} \bar{S}_a \times 10^{-6} \quad \ldots\ldots\ldots (3)$$

where V_0 = the value of c or the in-vacuo value of velocity adopted, f = the shoran timing-crystal frequency, k = the altitude of the ground station, H = the altitude of the shoran aircraft, $\Delta\mu$ = the increment of the index of refraction between the points selected for the numerical integration, and $\bar{S}_a$ = the computed minimum distance from the airplane to the ground station after correcting for the zero readings. Tables giving the distance increments on the various ray paths have been prepared for a large number of paths. Their use and the arrangement of calculations in a compact computing form make the entire integration process simple and straightforward.

The value of $\mu = 1.0002835$ for standard dry air at 760 mm pressure and 0°C temperature was originally used in the computation. An extensive investigation of all work which had been

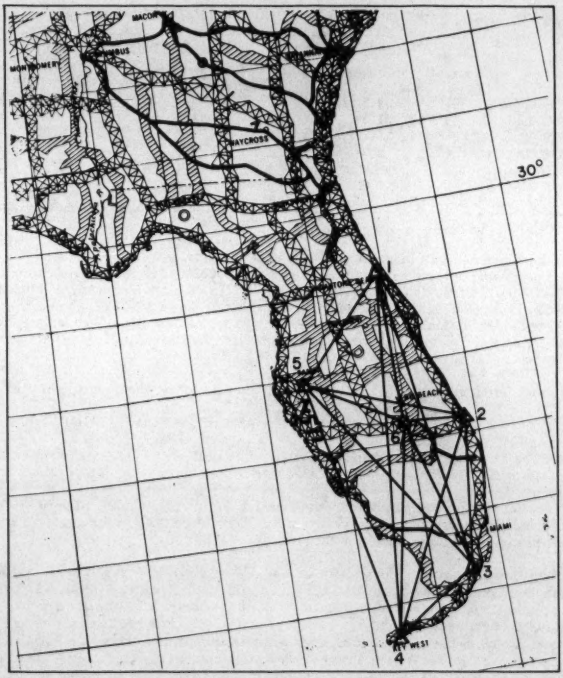


Fig. 1--Shoran scheme in Florida

Table 1--Comparison of geodetic distances with shoran determinations based on a velocity of 299,776 km/sec

Line	No. of crossings	Ground sta. no.		Distances		Shoran - geodetic
		Rate	Drift	Geodetic	Shoran	
				mi	mi	mi
2-6	13	2	3	40.6131	40.6041	-0.0090
3-4	12	1	3	96.7171	96.7049	-0.0122
5-6	11	1	2	100.3098	100.2988	-0.0110
5-1	12	1	3	118.9953	118.9840	-0.0113
1-6	12	1	2	133.0113	132.9985	-0.0128
2-3	12	2	3	134.9698	134.9546	-0.0152
5-2	12	1	3	139.1225	139.1127	-0.0098
3-6	17	1	2	145.8427	145.8276	-0.0151
1-2	18	3	2	145.8884	145.8768	-0.0116
4-6	11	1	2	190.5047	190.4889	-0.0158
2-4	12	1	2	199.1914	199.1735	-0.0179
5-3	14	2	3	226.9903	226.9698	-0.0205
5-4	11	1	2	235.5264	235.5042	-0.0222
1-3	12	2	3	277.0569	277.0347	-0.0222
1-4	13	1	2	320.1519	320.1271	-0.0248

Table 2--Summary of deviations from the mean

Deviation, mile	Individual line-crossings			Missions flown on different days		
	Number	Per cent	Cumulative per cent	Line no.	No. of missions	Average deviation, mile
0.0000 to 0.0010	97	54.2	54.2	3-4	9	0.0013
0.0011 to 0.0020	56	31.3	85.5	1-2	2	0.0025
0.0021 to 0.0030	21	11.7	97.2	3-6	2	0.0006
0.0031 to 0.0040	4	2.2	99.4	5-3	2	0.0012
0.0041 to 0.0050	0	0.0	99.4	5-4	4	0.0011
0.0051 to 0.0052	1	0.6	100.0		19	0.0013[a]
	179					

[a]Weighted mean.

done in the measurements of index of refraction and dielectric constant indicated that a statistical value of all preceding determinations would be about 1.0002875. A recent determination by BIRNBAUM, KRYDER, and LYONS [1951] gives a value for the dielectric constant of standard dry air as 1.0005763 or $\mu = 1.0002881$. Inasmuch as the value of $\mu = 1.0002876$, as determined from measurements in the optical band, lies between the above values, it was chosen and the originally computed lengths were changed to correspond with this value, which will be used in shoran work now in progress.

The interpolation equation currently in use to correct to the accepted velocity is

$$\Delta\mu \times 10^6 = 287.6 - 77.54\ P/T + 9.66\ e/T - 37.84\ e/(T/100)^2 \quad \ldots\ldots\ldots (4)$$

where $\Delta\mu$ = the change from the standard dry-air condition to the observed condition, P = the total pressure in mb, e = the water-vapor pressure in mb, and T = the temperature in °K.

The equation used in computing the values of $\Delta\mu$ in this paper differed very slightly from the above, the principal change being the change of the index of refraction for standard conditions, and corrections to distances were made for this change.

The distances measured--The project as a whole is shown in Figure 1. All stations were at or near triangulation stations of the U. S. Coast and Geodetic Survey. The inversed geodetic distances were computed using a modified Helmert method and are numerically exact to 0.0001 mile. The results of these measurements are tabulated in Table 1. Examination of the last column clearly shows the increase of the discrepancy with distance, which the writer attributes to the basic velocity error. However, the discrepancy in this column also includes a small constant error which was known to be about -0.0050 mile. In other words, each shoran ground station was known to measure about 0.0025 mile too short. The determination of these errors will be discussed later.

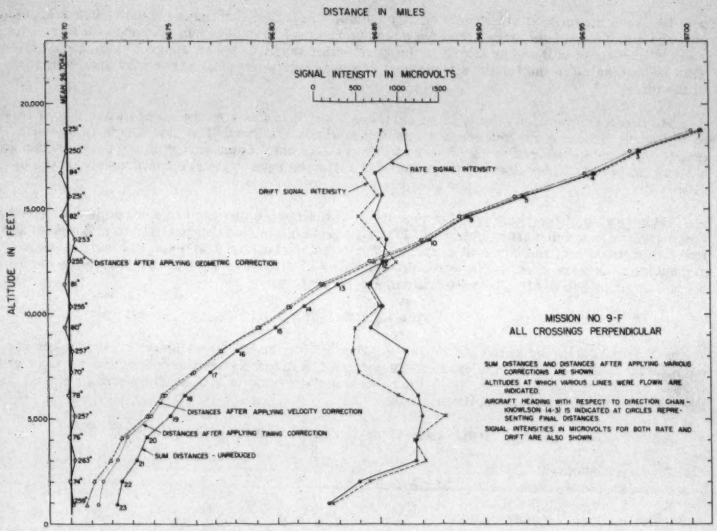

DISTANCE IN MILES
SIGNAL INTENSITY IN MICROVOLTS
0
500
1000
1500
ALTITUDE IN FEET
20,000
15,000
10,000
5,000
0
RATE SIGNAL INTENSITY
DRIFT SIGNAL INTENSITY
DISTANCES AFTER APPLYING GEOMETRIC CORRECTION
DISTANCES AFTER APPLYING VELOCITY CORRECTION
DISTANCES AFTER APPLYING TIMING CORRECTION
SUM DISTANCES - UNREDUCED
MISSION NO 9-F
ALL CROSSINGS PERPENDICULAR
SUM DISTANCES AND DISTANCES AFTER APPLYING VARIOUS CORRECTIONS ARE SHOWN
ALTITUDES AT WHICH VARIOUS LINES WERE FLOWN ARE INDICATED
AIRCRAFT HEADING WITH RESPECT TO DIRECTION CHAN - KNOWLSON 14-5) IS INDICATED AT CIRCLES REPRESENTING FINAL DISTANCES
SIGNAL INTENSITIES IN MICROVOLTS FOR BOTH RATE AND DRIFT ARE ALSO SHOWN

Fig. 2--Observed and corrected distances on a test mission

The internal consistency of the individual shoran line crossings was very high as shown by Table 2, which also illustrates that the repetitional accuracy of missions flown on different days is approximately the same as the internal consistency of a single mission. Numerous test missions which were not included in the record missions were flown. One of the most interesting ones was Mission 9-F, illustrated in Figure 2,which brought out three facts: (a) the validity of the gain-riding technique for removing the signal-intensity error, (b) the validity of the timing, velocity, and geometrical corrections, and (c) the first evidence of a multipath propagation effect.

Regarding (a) it is noted in Figure 2 that Line 3-4 was flown at 18 elevations at approximately 1000-ft intervals. In flying in this manner wide variations of signal intensity were encountered as shown in the figure. Yet there is no evidence that the absolute measurement was changed by this signal-intensity range.

Regarding (b) the successive corrections are applied to the original sum-distances with the final reduced distance resulting for each altitude. Again no correlation of reduced distance with altitude is encountered.

However, regarding (c) it is clearly evident that there is a correlation of aircraft heading with measured distance. The headings are shown for each reduced distance. It was clearly evident that this was not related to the signal intensity, and after much study it was demonstrated that this was a multipath propagation effect due to a combination of circumstances seldom encountered in practice. On this mission, the altitude of the airplane was such that a third re-radiated ray from a portion of the B-29 wing was responsible for this effect. The combination of circumstances resulting in such a condition is that, first, the ray re-radiated from the wing must be stronger in signal intensity throughout the crossing than the signal resulting from the phase combination of the direct ray and the ray reflected from the surface of the Earth. Secondly, this ray, which has a slightly longer path length, cannot exceed that path length by more than approximately 0.002 mile or its signal will be obliterated by the signal from the direct ray. Clearly, a mean of all crossings will differ little from a true value. However, a study of the antennae wiring and their placement was made, and before the record missions certain modifications were made in the equipment such that there is no evidence of this effect in the record missions. Indeed, a

portion of the directional effect may be attributable to the fact that these crossings were all nearly perpendicular crossings rather than the accepted figure-8 technique. In perpendicular crossing, a slight slackness in the gear trains of the goniometer might cause an apparent directional effect. This is eliminated in the figure-8 technique. An observer's personal error may also contribute to the effect.

Multipath propagation effects from surfaces other than those on the aircraft and the surface of the Earth can cause no concern when shoran methods are used. The path length is so much greater that it is obscured by the direct ray or appears only momentarily on the oscilloscope as a stray, whereas the resultant of the direct and reflected rays registers continuously on the oscilloscope.

Computation of the velocity--The results in Table 1 were analyzed to determine the velocity compatible with the distances obtained. It is also possible in this computation to make an analytical determination of the constant errors of each ground station. It is noted that only three shoran ground stations were used in the work. Inasmuch as 15 distances were measured, there are 15 observation equations in all. These equations are of the form

$$FS + K_1 + K_2 + E = 0$$

where F is the factor by which the shoran distances S [or the design velocity of 299,776 km/sec] must be increased to obtain the correct distance; K_1, K_2, and K_3 are the respective constant errors of ground stations 1, 2, and 3; and E represents the value of S-G, or the shoran reduced distance minus the inversed geodetic distance.

A least-square solution of the above 15 observations results in the following:

$F = 1.0000606 \pm 0.0000046$ or
$c = 299,776\ F = 299,794.2 \pm 1.4$ km/sec
$K_1 = -0.00193 \pm 0.00058$ mile
$K_2 = -0.00369 \pm 0.00073$ mile
$K_3 = -0.00200 \pm 0.00053$ mile

Thus

$K_1 + K_2 = -0.0056$ mile
$K_1 + K_3 = -0.0039$ mile
$K_2 + K_3 = -0.0057$ mile
Probable error of a shoran measurement = $\pm$ 0.00118 mile

The values of the combinations of the constant ground-station errors must be applied to the shoran measured distances. The values obtained in the solution are negative. The errors are of opposite sign and the shoran distances must be increased by the amount of the factor F and the constant errors to give the correct distances. The velocity designed into the instrument must also be increased by the factor F.

Determination of local survey error by shoran measurements--An interesting example of the confidence of the writer in the shoran measurements occurred during the course of the project. Examination of Figure 1 shows that five distances are measured to each point. When the shoran measurements were first compared with the geodetic distances, the results at Station (4) near Key West were not compatible with the results of the remaining 10 lines. This discrepancy is best illustrated by reference to Figure 3. Therefore, a preliminary adjustment was made assuming a single constant error for all combination ground stations and the amount of movement of Station (4) necessary to bring it into agreement with the remaining shoran distances was computed. The following observation equations were used.

For lines not including Station (4) the equations took the form

$$FS + K + E = 0$$

For lines including (4), two additional terms were added to allow for shift of Station (4) and the equations were of the form

$$FS + K + d\,[\cos(\alpha - \beta)] + E = 0$$

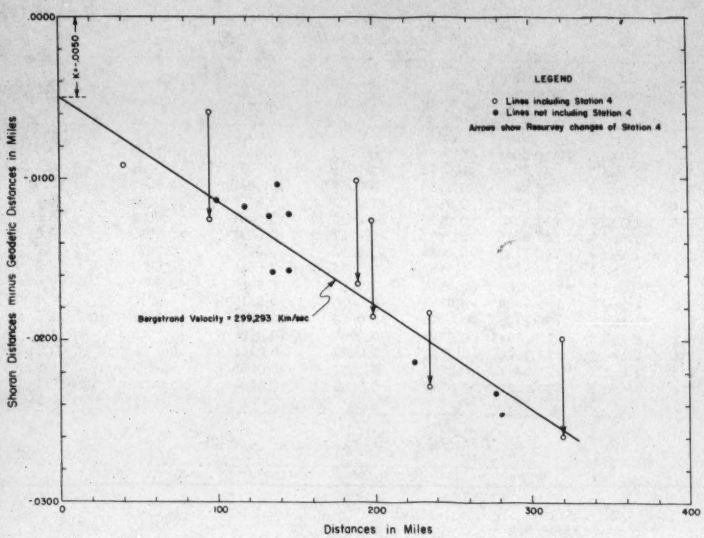


Fig. 3--Shoran distances minus geodetic distances prior to resurvey of Station 4 at Key West

F, S, K, and E have been defined, d is the distance station (4) should be moved, α is the azimuth of the line from Station (4) to the remote ground station, and β is the azimuth of the short distance joining the new position of (4) to the original position.

This adjustment resulted in the following determinations: d = 0.0067 mile and β = 219 3/4°, or β - 180° = 39 3/4°.

As a result of the above computation, the writer in a written report recommended that a resurvey be made at Key West. This resurvey was made several months later by the U. S. Coast and Geodetic Survey. The error predicted by the writer in the above adjustment was verified and the results were: d = 0.0069 mi and β = 37.0°.

Thus a local survey error was predicted within two feet by five shoran measurements which varied from 96 to 320 miles. This instance supports the value of the velocity of radio waves derived from shoran measurements.

In fairness to the local survey party it should be stated here that the error was not in their field work but was caused by the fact that they tied to a single reference mark which had evidently been disturbed; the original station mark was lost.

Results--The results computed from the final values are shown graphically in Figure 4. In that figure the analytically determined values of the constant error have been applied. The final tabulated results of the adjustment are shown in Table 3. The mean proportional error of about 9 parts in 10^6 is clearly compatible with the figure of $\pm$ 1.4 km/sec derived as the probable error of the velocity determination from the computation, when it is considered that 15 measurements were made.

Recent published determinations of c--ESSEN [1951] tabulated the values shown in Table 4. The writer believes that the value of 299,794.2 $\pm$ 1.4 as published in this paper is far better than the previous value obtained from the earlier shoran work and that it should also be included in

Table 3--K and F corrections and residual errors (v's) derived from the adjustment by least squares

Line	Ground station numbers	Shoran distance (s)	Shoran minus geodetic distance	Correction for K	Correction for F (F-1)s	v's from adjustment	Proportional error
		mi	mi	mi	mi	mi	(parts in 10^6)
2-6	2 and 3	40.6041	-0.0090	+0.0057	+0.0025	+0.0008	19.7
3-4	1 and 3	96.7049	-0.0122	+0.0039	+0.0059	+0.0024	24.8
5-6	1 and 2	100.2988	-0.0110	+0.0056	+0.0061	-0.0007	7.0
5-1	1 and 3	118.9840	-0.0113	+0.0039	+0.0072	+0.0002	1.7
1-6	1 and 2	132.9985	-0.0128	+0.0056	+0.0081	-0.0009	6.8
2-3	2 and 3	134.9546	-0.0152	+0.0057	+0.0082	+0.0013	9.6
5-2	1 and 3	139.1127	-0.0098	+0.0039	+0.0084	-0.0025	18.0
3-6	1 and 2	145.8276	-0.0151	+0.0056	+0.0088	+0.0007	4.8
1-2	3 and 2	145.8768	-0.0116	+0.0057	+0.0088	-0.0029	19.9
4-6	1 and 2	190.4889	-0.0158	+0.0056	+0.0115	-0.0013	6.8
2-4	1 and 2	199.1735	-0.0179	+0.0056	+0.0121	+0.0002	1.0
5-3	2 and 3	226.9698	-0.0205	+0.0057	+0.0138	+0.0010	4.4
5-4	1 and 2	235.5042	-0.0222	+0.0056	+0.0143	+0.0023	9.8
1-3	2 and 3	277.0347	-0.0222	+0.0057	+0.0168	-0.0003	1.1
1-4	1 and 2	320.1271	-0.0248	+0.0056	+0.0194	-0.0002	0.6
					Means	0.00118	9.1

Table 4--Velocity of waves in vacuo (c)

Author	Method	Velocity in vacuo	Weight
		km/sec	
Birge	Optical	299,776 ± 4	1
Essen and Gordon-Smith	Cavity resonator	299,792 ± 9	1
Bergstrand	Optical	299,793.1 ± 0.25	2
Aslakson	Shoran	299,792 ± 2.4	2
Essen	Cavity resonator	299,792.5 ± 3	2
Bol	Cavity resonator	299,789.3 ± 0.4	2
	Resultant mean value	299,790.2	

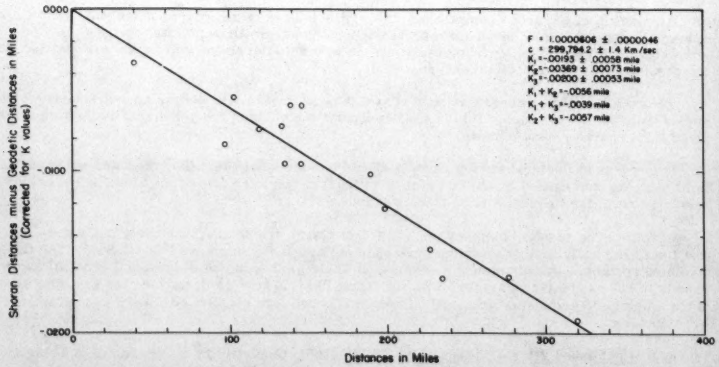


Fig. 4--Adjusted shoran results assuming a separate K for each ground station

any proposed value for c. In fact, the evidence now is very strong that the Birge statistical value should be abandoned entirely. A detailed examination of all of the results of the individual observers included in the determination of that value reveals a lack of consistency far below that obtained by recent observers. An average of the latest observations results in a new value of 299,792.2 which, in view of the better consistency of recent work, seems to be a reasonable figure to adopt for the present.

It can now be stated that, in shoran work in progress, a value of 299,793 km/sec is being used in the computations and to date excellent checks are being obtained in comparison with surveyed distances. During the present work at least 9 to 11 new distance comparisons will be made.

References

ASLAKSON, CARL I., and DONALD A. RICE, Use of shoran in geodetic control, Trans. Amer. Geophys. Union, v. 27, pp. 459-463, 1946.

ASLAKSON, CARL I., Can the velocity of radio waves be measured by shoran?, Trans. Amer. Geophys. Union, v. 30, pp. 475-487, 1949.

ASLAKSON, CARL I., and OMAR O. FICKEISSEN, The effect of meteorological conditions on the measurement of long distances by electronics, Trans. Amer. Geophys. Union, v. 31, no. 6, pp. 816-826, 1950.

ASLAKSON, CARL I., Some aspects of electronic surveying, Proc. Amer. Soc. Civil Eng., v. 77, Separate no. 52, Jan. 1951.

BIRGE, R. T., The general physical constants as of August 1941 with details on the velocity of light only, Rep. Phys. Soc. Prog. Phys., v. 8, pp. 90-134, 1942.

BIRNBAUM, GEORGE, S. J. KRYDER, and HAROLD LYONS, Microwave measurements of the dielectric properties of gasses, J. of Appl. Physics, v. 22, pp. 95-102, 1951.

ESSEN, L., Proposed new value for the velocity of light, Nature, v. 167, pp. 258, Feb. 17, 1951.

KROLL, C. W., A rigorous method for computing geodetic distance from shoran observations, Trans. Amer. Geophys. Union, v. 30, pp. 1-4, 1949.

U. S. Coast and Geodetic Survey,
Washington 25, D. C.

(Communicated manuscript received May 5, 1951;
open for formal discussion until May 1, 1952.)

Transactions, American Geophysical Union Volume 32, Number 6 December 1951

RAYLEIGH WAVES FROM SMALL EXPLOSIONS

M. B. Dobrin, R. F. Simon, and P. L. Lawrence

Abstract--As part of a program to study ground disturbances that interfere with seismic prospecting, an experimental seismic crew of the Magnolia Petroleum Co. has been investigating Rayleigh waves from shot-hole explosions at distances up to about 3000 ft. Waves have been recorded by vertical and horizontal geophones through a system giving flat response between 5 and 200 cycles/sec. The geophones have been disposed along surface profiles with separations that are short compared to Rayleigh wavelengths and also at various depths up to 100 ft in boreholes. Rayleigh waves from air explosions have also been recorded.

Sample arrays of records are presented on which individual waves from hole and air shots can be followed for horizontal distances up to about ten wavelengths. Dispersion characteristics observed on the records are plotted in a form permitting comparison with theoretical dispersion curves for various kinds of surface layering. Effects of varying the depth of the explosion are observed and compared with theoretical predictions. Particle-motion trajectories are plotted both at the surface and at various depths. Results all show as good agreement with classical theory as can be expected in view of the simplifying assumptions which must be made in deriving this theory.

Constant-frequency wave trains were observed immediately after the air-wave arrival on the records made from single air explosions eight feet above the ground. These are shown to be waves of the type predicted by the Press-Ewing theory of surface-wave coupling to the atmosphere.

Introduction

During the past several years an experimental seismic crew operated by the Field Research Laboratories of the Magnolia Petroleum Co. has carried on extensive field studies of surface waves generated by explosions of the type employed in seismic prospecting. The principal application of this work has been to devise means of eliminating waves that can interfere with the recording of reflections in prospecting operations. In the course of its investigations this group has obtained considerable data which might be of interest to those concerned with the much larger scale surface waves obtained from earthquakes. A comparison of both types of waves from the standpoint of classical theory may cast light on the mechanism of wave propagation in each case.

LEET [1939] and HOWELL [1949] have recorded surface waves near explosions with three-component detecting instruments, have identified various types of waves on their records, and have compared their observations on velocities, frequencies, and wave forms with the predictions based on classical wave theory developed to explain the data of earthquake seismology. Although qualitative similarity was observed, disagreements were also noted which could only be explained by the fact that near-surface earth materials do not have the elastic properties of the ideal solids assumed in the theoretical treatments.

Our investigations of surface waves have involved several features which we believe to be novel. Studies have been carried on in a variety of areas giving opportunity to observe waves at locations with widely divergent near-surface lithologies. Experimental profiles have been located over surface layers consisting of clay, loose sand, weathered shale, and high-speed limestone. The seismic properties of the surface layer and substratum have been specified in each case by logs of compressional and shear velocities. A recording setup was employed which made it possible to follow individual waves for distances up to about ten wavelengths. This involved continuous use of detector spacings that were small compared with the wavelength. Borehole tests with three-component geophones gave data on surface-wave characteristics to depths of about half a wavelength. Dispersion theory has been employed to relate the wave observations to the elastic characteristics of the near surface. Finally, we have obtained the first experimental confirmation of the Press-Ewing theory of air coupling [see PRESS and Others, 1951] as it relates to surface waves in a layered earth.

Although a number of different surface-wave types have been observed and investigated, we will confine the present discussion largely to our observations on Rayleigh waves. Most of the field data to be presented here have been taken from only one of our experimental locations.

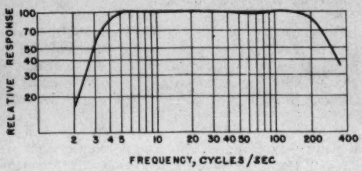


Fig. 1--Frequency-response curve for overall system, including geophone, amplifier, and galvanometer

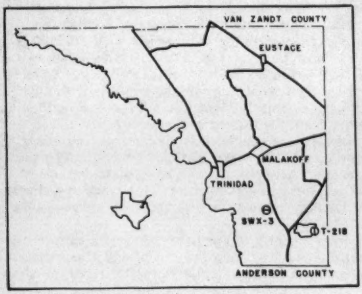


Fig. 2--Western part of Henderson County, Texas, showing locations at which surface-wave experiments were conducted

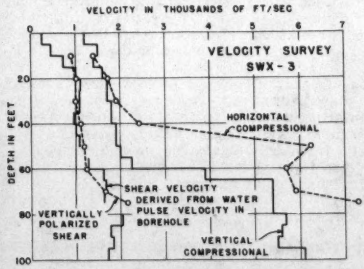


Fig. 3--Logs of compressional and shear interval velocities at SWX-3

Experimental procedure

Instruments--The instrumental system employed in these experiments is similar in most respects to that used in prospecting operations. The band of frequency response is considerably wider, however, than in standard seismic equipment; also, horizontal detectors were used as well as the vertical type. Figure 1 shows a response curve of the entire system, including the geophone, amplifier, and galvanometer. The response is essentially flat between 5 and 200 cycles/sec. The geophones, both horizontal and vertical, were of the electromagnetic type and were especially designed for low-frequency measurements by G. B. Loper, R. R. Pittman, and S. N. Heaps of the Magnolia Field Research Laboratories.

Location--Most of the data to be presented here come from an experimental profile designated as SWX-3, located in the southern portion of Henderson, County, Texas (see Fig. 2). To obtain information on the elastic properties of those formations close enough to the surface to control Rayleigh-wave characteristics, borehole logs were made of horizontal and vertical compressional and shear velocities down to 100 ft. The techniques for obtaining such logs have been discussed by J. E. White of Magnolia in a paper given at the meeting of the Society of Exploration Geophysicists in 1951. Figure 3 shows these logs, which indicate a sharp discontinuity in compressional speed at 60 ft with a much less pronounced discontinuity in the shear velocity.

Shooting procedure--Three types of tests will be discussed in this paper:

(1) Ground motion from dynamite explosions in boreholes 40 ft or more deep was recorded by geophones disposed along a profile about 3000 ft long. Five-pound charges were generally used. Each spread corresponding to a single record was 450 ft long and consisted of a three-component cluster (containing vertical, horizontal radial, and horizontal transverse geophones) at one end and nine vertical phones spaced at 50-ft intervals. The last vertical phone of each spread coincided in position with the three-component cluster beginning the next spread. Seven records were required to permit continuous correlation along a 3000-ft profile in this manner.

(2) An array of records was made with the same disposition of geophones from an explosion of five pounds of dynamite eight feet in the air on a stake located at the same position as the shot hole. The purpose was to compare surface waves from a hole shot with those from an air explosion.

(3) A series of hole shots was recorded by a three-component group of geophones lowered into a 100-ft borehole at a distance of 1900 ft from the shot point. Records were made at ten-foot depth intervals to 100 ft. The geophones were mounted on a frame oriented by loading poles and coupled to the earth at the desired depth by a spike penetrating the side of the borehole.

Rayleigh waves recorded at surface from hole shots

Record arrays--Figure 4 is a reproduction of a record array showing the ground motion resulting from hole shots up to distances of 3000 ft. The first two traces of each record show horizontal radial and horizontal transverse motion at the nearest detector position of the spread; the remaining ten show vertical motion at 50-ft intervals. This arrangement gave a complete picture of the particle motion every 450 ft along the profile and made it possible to follow waves having vertical components of motion for its entire length.

The high-amplitude, more or less sinusoidal waves observed on the later portion of each record, with an onset designated by R, are identified as Rayleigh waves since the particle motion is in the vertical plane and is retrograde elliptical as called for by theory [RAYLEIGH, 1885]. The regular increase in the length of the Rayleigh wave train with increasing shot-receiver distance is attributable to dispersion, a feature to be discussed in some detail shortly.

Time-distance plot--All individual peaks that can be followed across one or more records are shown on a time-distance plot (see Fig. 5). The earliest event observable on each trace is the first compressional arrival, the wave evidently refracted in the high-speed (6000 to 7200 ft/sec) material just below the unconsolidated layer indicated on the logs (see Fig. 3). Subsequent waves with approximately the same apparent speed are believed to be multiply refracted from the base of the low-speed zone. The short segments observed somewhat later on the records with apparent speeds ranging from 2800 to 4000 ft/sec have not been definitely identified but the suggestion has been made that they are shear waves refracted or multiply reflected at the base of the low-speed surface layer. The earliest identifiable Rayleigh waves are represented by the long segments with an apparent speed of 1600 ft/sec for distances up to 1000 ft and with speeds of 1850 ft/sec and then 2200 ft/sec at successively greater distances. All subsequent waves, up to 4.5 sec at 3000 ft, have Rayleigh-type particle motion. The decrease of apparent Rayleigh wave speed with time at any given distance is further evidence of the dispersive nature of the wave propagation.

Dispersion--The variation in the phase and group velocity of the Rayleigh waves with frequency has been determined by two methods. By the first method the group velocity of any given wave was determined by measuring the time of its occurrence on the record and dividing this into the shot-receiver distance. The phase velocity was obtained from the slope of the time - distance segment corresponding to the wave at the distance represented by the trace. Because of a certain irregularity in the data points for the time - distance curve, phase-velocity determination by this method was not very accurate. Periods for each wave cycle were determined by plotting the time of each peak (or trough) against the ordinal number of the feature, drawing the best smooth curve through the plotted points and taking the slope of the curve at the time corresponding to the cycle in question. Figure 6 shows the group velocity-period relationship as computed directly from the records for various shot-receiver distances ranging from 750 to 2800 ft. The points show that within these limits there is little dependence of the velocity-frequency relationship upon distance.

The most satisfactory method for determining the phase velocity - frequency curve is Fourier analysis. With this technique one ascertains the phase shift at each frequency between the waves recorded at two positions along the profile by converting the phase angle into an equivalent time to be divided into the distance between the two locations. A curve of phase velocity versus frequency, period, or wavelength can be plotted over the frequency range within which the Rayleigh-wave spectrum is confined. The group velocity - dispersion curve can be obtained by graphical differentiation of the phase velocity - wavelength curve using the relation

$$U = C - \lambda \, dC/d\lambda$$

where U is group velocity, C phase velocity, and λ wavelength.

Figure 7 shows dispersion curves for SWX-3 as determined by Fourier analysis of records made at 800 and 1200 ft. The group velocities here show quite close agreement with those determined directly from the records and plotted in Figure 6.

The dispersion of Rayleigh and Love waves is governed by the layering in the near-surface material, specifically by the thickness of the layers and the contrast in densities and elastic constants between the layer or layers and the material below. The theoretical relations have been worked out by Jeffreys, Stoneley, Sezawa, Lee, and others; a list of references to the literature on Rayleigh-wave dispersion is available in a review by DOBRIN.[1951]. For many years, seismologists have studied the layering of the Earth's crust by analyzing the dispersion characteristics of Rayleigh and Love waves from earthquakes. Because of the many variables involved, it

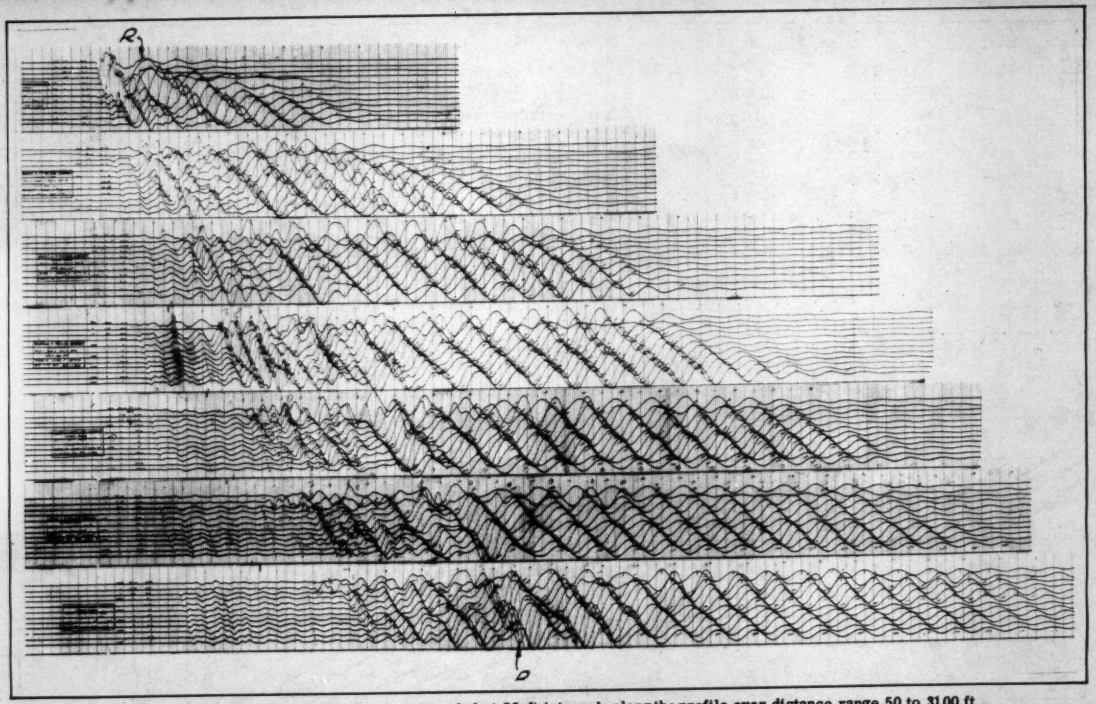


Fig. 4--Record array showing surface waves recorded at 50-ft intervals along the profile over distance range 50 to 3100 ft from shot; the first three traces of each record show respectively the horizontal radial, horizontal transverse, and vertical motion at stations spaced every 450 ft; the remaining traces show vertical motion every 50 ft; the last trace of each record duplicates the third trace (first vertical trace) of the next record)

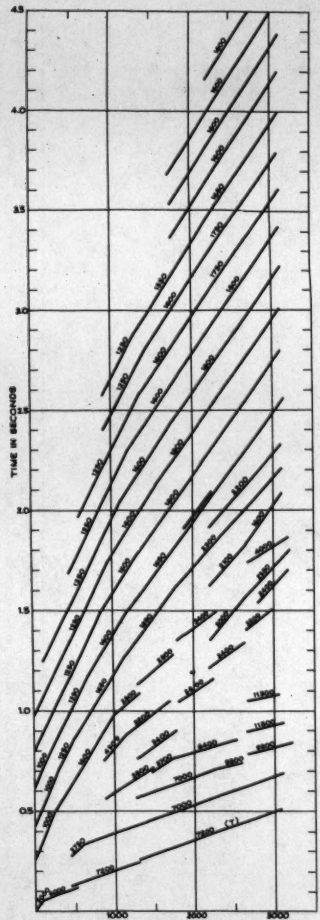


Fig. 5--Time - distance plot for surface waves at SWX-3 shown on record array in Figure 4

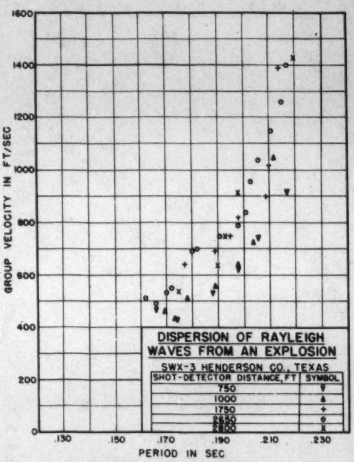


Fig. 6--Group velocity - period relations observed on SWX-3 records as determined by direct measurement of travel times

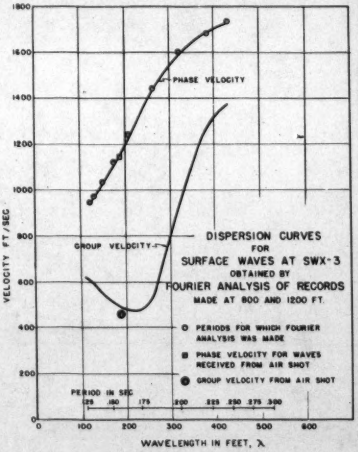

VELOCITY FT./SEC
WAVELENGTH IN FEET, λ
PHASE VELOCITY
GROUP VELOCITY
DISPERSION CURVES FOR SURFACE WAVES AT SWX-3 OBTAINED BY FOURIER ANALYSIS OF RECORDS MADE AT 800 AND 1200 FT.
PERIODS FOR WHICH FOURIER ANALYSIS WAS MADE
PHASE VELOCITY FOR WAVES RECEIVED FROM AIR SHOT
GROUP VELOCITY FROM AIR SHOT
PERIOD IN SEC

Fig. 7--Group and phase velocities at SWX-3 as function of wavelength and period as determined by Fourier analysis

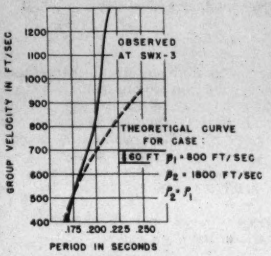


Fig. 8--Comparison of observed dispersion curve with theoretical curve based on calculations of Sezawa for layered solid with indicated characteristics

is not possible to arrive at a unique solution by this means. If, however, there is independent control that permits reasonable assumptions regarding some of the variables, dispersion data can give otherwise unobtainable information on the composition and dimensions of the Earth's superficial layers. To compute a theoretical dispersion curve for the case of Rayleigh waves in a solid layer over a solid substratum is such a tedious operation that such curves are only available for a small number of cases.

To analyze the factors controlling the dispersion observed at SWX-3, a survey was made of all published dispersion curves for two solid layers to find out which assumptions as to layering would give the closest fit to the observed dispersion. In Figure 8 the dispersion curve obtained from the records at SWX-3 is compared with a theoretical curve based on computations by SEZAWA [1927] for a two-layer case which comes closest to fitting that indicated for SWX-3 by the log shown in Figure 3. Although the agreement is not perfect, deviations are not large and can probably be explained by the obvious departures of the actual velocity distribution from that postulated for the theoretical curve; also by the fact that Poisson's ratio is not 0.25, the value assumed in deriving the theoretical curves, for unconsolidated materials such as are in the near-surface layers.

It thus appears that the dispersion characteristics of Rayleigh waves recorded near a shot-hole explosion can be explained as the effect of near-surface layering. One interesting corollary is that variations in shear velocity rather than in compressional velocity appear to control the dispersion. This is in accordance with theory, since LOVE [1911] has shown that very large variations in compressibility have but a negligible effect on Rayleigh-wave propagation. It might appear from this study that dispersion curves could constitute an effective tool for studying the superficial layers near the surface of the ground, particularly as regards the distribution of shear speeds. Unfortunately, the usefulness of this method is limited by the ambiguity to which it is subject; it should, however, give fairly reliable information when, as in the earthquake case, there is independent control on most of the variables. For present purposes the dispersion study has its greatest value in demonstrating that propagation of Rayleigh waves in the four to six cycles-per-second region is influenced by superficial layers tens of feet thick in the same way that the much longer waves observed from earthquakes are affected by crustal layering tens of kilometers in thickness.

Effect of shot depth--It has long been recognized that Rayleigh waves from deep-focus earthquakes are much weaker than from those with shallow foci. BANERJI [1925] and JEFFREYS [1929] have shown that in a homogeneous medium the amplitude of these waves should decrease with source depth z as

$$e^{-Kz/\lambda}$$

where λ is wavelength and K is 5.8 for a purely compressional source disturbance and 2.4 for a purely distortional one. If the disturbance generates both types of movement, the coefficient should be between these limits.

To test the application of this relationship to Rayleigh waves from a shot-hole explosion, let us consider some data obtained when a series of shots was fired at depths ranging from one to 300 ft, the ground motion being received by a spread of vertical geophones 1550 to 1725 ft away. This test was at a location, designated as T-218, about five miles from SWX-3 (see Fig. 2) where the previously described experiments were conducted. The near-surface lithology at T-218 is about the same as at SWX-3, but the low-speed zone is only about 20 ft thick.

Figure 9 illustrates the variation of maximum Rayleigh-wave amplitude with shot depth. In the superficial layer, the amplitude increases with depth of shot; this is attributed to the more efficient transmission of energy into the Earth as consolidation increases with depth within the layer. At the 20-ft discontinuity, the degree of consolidation is no longer sensitive to depth. Between this depth and 300 ft the Rayleigh-wave amplitude, A, falls off according to the relation

$$A = Ce^{-0.012z}$$

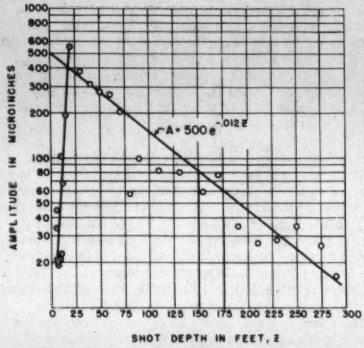


Fig. 9--Variation of Rayleigh-wave amplitude from five-pound explosion as function of depth of shot; data from T-218

or since the wavelength here is about 300 ft,

$$A = Ce^{-3.6\,z/\lambda}$$

Comparing the coefficient 3.6 with the respective values for a purely compressional source (5.8) and for a purely distortional one (2.4), it appears that a buried explosion gives both types of disturbance. No further quantitative comparisons are warranted in view of the layering and other inhomogeneities which violate the assumptions upon which the theory is based.

Trajectories of particle motion in Rayleigh waves

The use of three geophones, all close together, for simultaneous recording of ground motion in mutually perpendicular directions has made it possible to plot particle trajectories during passage of a Rayleigh wave, both on the surface and in boreholes. For a homogeneous solid with a Poisson's ratio of 0.25, Rayleigh's theory predicts that the motion on the surface will be retrograde and elliptical with the major axis vertical and 1.45 times the minor (horizontal) axis in amplitude. The effect of layering on the ratio of horizontal to vertical amplitudes on the surface is complex and difficult to predict, as has been demonstrated by LEE [1934]. In the absence of layering, the amplitude should fall off exponentially with depth. The horizontal component becomes zero at a depth of 0.192 wavelengths [BYERLY, 1942, p. 173] and changes sign at greater depths. Since the vertical component never changes sign, the trajectory should shift from retrograde (counterclockwise, if the source is to the left) to direct (clockwise) at this depth.

The ground-motion trajectories to be presented here were obtained with the three geophones lowered into a borehole on a frame clamping into the wall of the hole. The results obtained in this way for very shallow depths essentially duplicate those obtained with conventional plants of corresponding geophones on the surface.

Figure 10 shows the particle-motion trajectories observed at a ten-foot depth 1900 ft from the shot point at SWX-3. Five successive cycles are represented. The motion is retrograde in all cases and is approximately elliptical. The axes of the ellipses are not exactly vertical as theory requires but tend to shift in direction from cycle to cycle, showing a tilt that becomes progressively more clockwise with time. Axial rotation of this kind has been often observed on Rayleigh waves from earthquakes but has, as far as is known, not been explained.

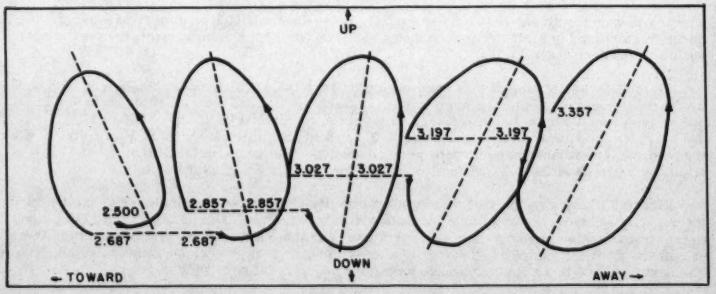


Fig. 10--Particle trajectories of successive Rayleigh-wave cycles recorded at ten-foot depth; SWX-3

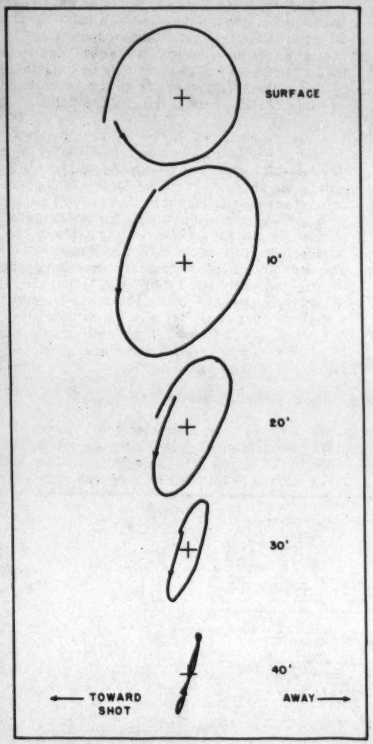


Fig. 11--Particle trajectories of Rayleigh waves recorded at ten-foot depth intervals from 0 to 40 ft; SWX-3

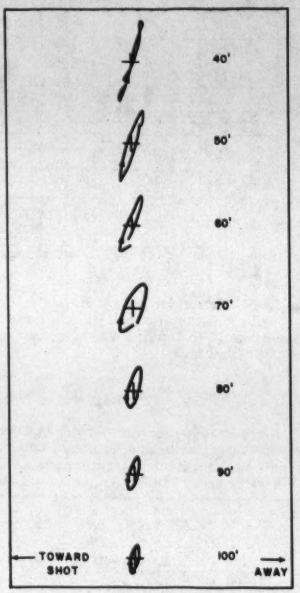


Fig. 12--Particle trajectories of Rayleigh waves recorded at ten-foot depth intervals from 40 to 100 ft; SWX-3

Figures 11 and 12 show how the particle-motion trajectory changes with depth at ten-foot intervals up to 100 ft. On the surface the motion is almost circular; the vertical axis becomes longer with respect to the horizontal as depth increases. The increase in apparent amplitude at ten feet is explained on the basis of the more efficient clamping at this depth allowed by greater consolidation of the sediments. At about 40 ft the motion becomes linear, in an approximately vertical plane, changing at this depth from counterclockwise to clockwise. The crossover depth, theoretically at 0.192 wavelengths, is observed to shift to progressively shallower depths for successive wave cycles which because of dispersion have a successively shorter wavelength. The relations are shown in Table 1.

Table 1--Relation of depth to particle motion

Cycle	Depth of linear motion	Wavelength	Crossover depth in wavelengths
	ft	ft	
1	44	324	0.136
2	42	307	0.137
3	40	280	0.138
4	37	273	0.135
5	35	257	0.136

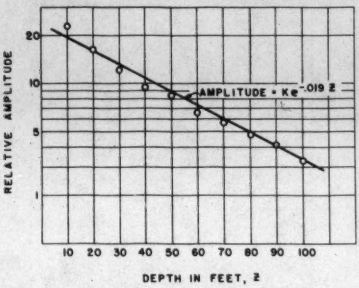


Fig. 13--Effect of depth upon the vertical component of the amplitude of Rayleigh waves in the range 10 to 100 ft; SWX-3; measurements 1900 ft from shot

The ratio of crossover depth to wavelength is seen to stay quite constant at a value about 30 pc. smaller than predicted by theory for a homogeneous medium with a Poisson's ratio of 0.25. The deviation can probably be explained by the obvious departures from the assumptions on which the theoretical figures are based.

Figure 13 shows the variation in the amplitude of vertical motion as a function of depth. The fall-off appears to be exponential, the amplitude varying as $e^{-0.019z}$ where z is depth. It is interesting to compare this fall-off relation with the one obtained at T-218 for decrease of surface amplitude with increasing depth of the source. The fall-off in that case was as $e^{-0.012z}$. The decrements are sufficiently close to confirm the suggestion by JEFFREYS [1927] that the fall-off of Rayleigh-wave amplitude on the surface with increasing focal depth is the same as the fall-off observed in the ground-motion amplitude of a Rayleigh wave from a fixed source when measured at increasing depths below the surface.

Rayleigh waves from air explosions - coupled waves

Early in 1950, some experiments were conducted by a group from Columbia University and the Air Force Cambridge Research Laboratories on the propagation of seismic waves in floating ice on Lake Superior. Measurements were made on the ice of waves generated by explosions both in the water under the ice and in the air above it. In the course of this work a new type of wave

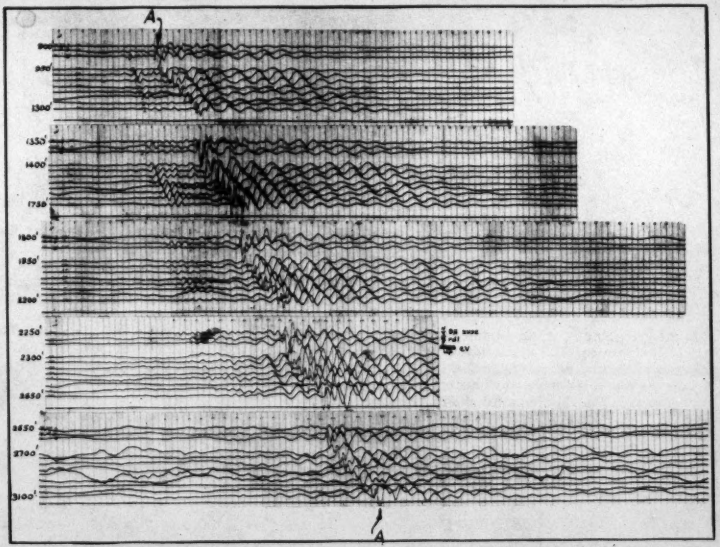


Fig. 14--Record array showing surface waves received from single air shot at 50-ft intervals over the range 900 to 3100 ft from shot at SWX-3; geophone setup is the same as that for records of hole shots shown in Figure 4

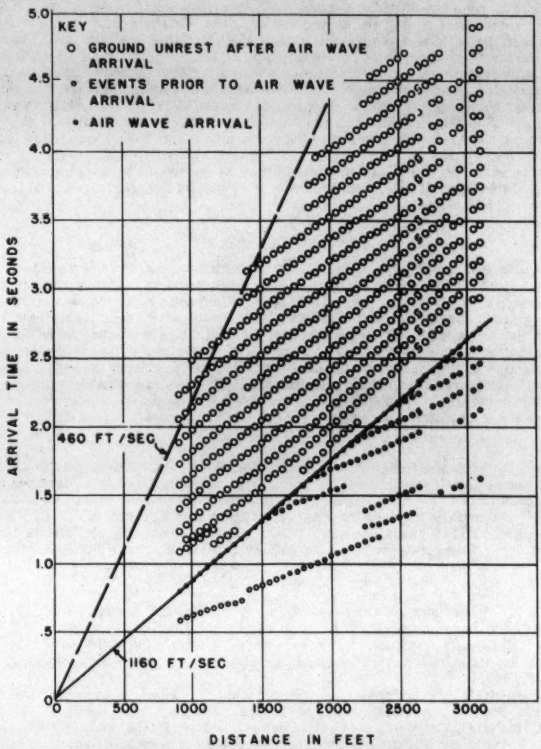


Fig. 15--Time-distance plot for air shooting records shown in Figure 14; full line represents arrival of air wave

was discovered which resulted from the air explosions over the ice [PRESS and Others, 1951]. The theoretical explanation worked out by PRESS and EWING [1951] for these waves led them to predict that a similar type of wave could be observed, under specified conditions, from air shooting with geophones on the ground. This wave results from the coupling of energy into the Earth from the air wave that spreads out from the shot and it is observed only when the phase velocity of dispersive surface waves (such as the flexural waves in ice or Rayleigh waves in a layered Earth) is equal at some frequency to the velocity of sound in air. When this condition is met, the air-coupled wave, as they call it, will have this phase velocity and a constant frequency equal to that at which the dispersive wave has the air-wave phase velocity. In the case of air-coupled Rayleigh waves, it was predicted that the onset would coincide with the arrival of the air wave and the termination would be at the group velocity corresponding to this frequency.

The existence of air-coupled waves over a layered Earth was first demonstrated by the Magnolia experimental seismic crew in the course of some experiments suggested by theoretical predictions of Ewing and Press. Subsequently, Press, working as a consultant for Magnolia, suggested further experiments and worked out a theory for "ground roll" from air shots. He presented this theory in a paper given at the meeting of the Society of Exploration Geophysicists in 1951, and illustrated it with some data obtained by the Magnolia crew. For this reason this discussion will be limited to a brief demonstration of some data on air-coupled waves as observed at SWX-3.

Figure 14 is an array of records made with a geophone setup identical to that shown earlier (see Fig. 4) and with the shot at the same location but on a stake eight feet in the air rather than in a borehole. The surface-wave picture is quite different from that shown in Figure 4. Until the arrival of the air wave, designated by the letter A, no long-period waves are observed at all, but immediately thereafter we see a train of waves with a uniform period of 0.157 sec. These waves have the same step-out velocity as the air wave and an inspection of Figure 7 shows that at a period of 0.157 sec the phase velocity for Rayleigh waves is 1150 ft/sec, which was the velocity of sound in air on the day the shooting was carried on. These waves fulfill all the criteria established by Ewing and Press for coupled waves and can be identified as such with confidence.

Figure 15 shows the time-distance curve for this record array and demonstrates how the termination of the coupled waves appears to be at a velocity that corresponds to the group velocity for a wave of 0.157-second period (see Fig. 7).

Conclusion

The experiments reported upon here illustrate how Rayleigh waves generated by a shot-hole explosion can have all the essential characteristics predicted by classical wave theory. Although there are quantitative discrepancies between observation and prediction, deviations of the same order of magnitude have been noted in the data on Rayleigh waves from earthquakes. In both cases, the differences can be explained by the fact that the actual conditions are more complex than those assumed in the theoretical derivations. Layering, irregularities in geometry, and departure of the elastic properties of semi-consolidated near-surface materials from those of "ideal solids" would make a complete theoretical analysis of actual Rayleigh-wave propagation in nature a most formidable undertaking. In view of this it is interesting and instructive to observe the essential applicability of Rayleigh-wave theory to two cases in which the scale factor differs by the order of 1:3000.

Acknowledgment--The field data reported in this paper were obtained by the Magnolia Field Research Laboratories' experimental seismic party. Substantial contributions were made by the following members of this group: H. H. Frost (party chief), Warren Hicks, R. L. Sengbush, and A. G. Hubby. The authors express their appreciation to D. H. Clewell and J. E. White of the Magnolia Laboratories and to Frank Press of Columbia University for helpful discussions; also to the management of the Magnolia Petroleum Co. for permission to submit this paper for publication.

References

BANERJI, S. K., On the depth of earthquake focus, Phil. Mag., v. 49, pp. 65-80, 1925.

BYERLY, PERRY, Seismology, Prentice-Hall, New York, 1942.

DOBRIN, M. B., Dispersion in seismic surface waves, Geophysics, v. 16, pp. 63-80, 1951.

HOWELL, B. F., JR., Ground vibrations near explosions, Bull. Seis. Soc. Amer., v. 39, pp. 285-310, 1949.

JEFFREYS, HAROLD, The times of transmission and focal depths of large earthquakes, Mon. Not. R. Astron. Soc., Geophys. Sup., v. 1, pp. 500-521, 1927.

JEFFREYS, HAROLD, The Earth (2nd ed.), Cambridge Univ. Press, 1929.

LEE, A. W., Further investigation of the effect of geological structure upon microseismic disturbance, Mon. Not. R. Astron. Soc., Geophys. Sup., v. 3, pp. 238-252, 1934.

LEET, L. D., Ground vibrations near dynamite blasts, Bull. Seis. Soc. Amer., v. 29, pp. 487-496, 1939.

LOVE, A. E. H., Some problems in geodynamics, Cambridge Univ. Press, 1911.

PRESS, F., A. P. CRARY, S. KATZ, and J. OLIVER, Air-coupled flexural waves in floating ice, Trans. Amer. Geophys. Union, v. 32, pp. 166-172, 1951.

PRESS, F., and M. EWING, J., Theory of air-coupled flexural waves, J. Appl. Phys., V. 22, pp. 892-899, 1951.

RAYLEIGH, LORD, On waves propagated along the plane surface of an elastic solid, Proc. London Math. Soc., v. 17, pp. 4-11, 1885.

SEZAWA, K., Dispersion of Rayleigh waves propagated on the surface of stratified bodies and curved surfaces, Bull. Earthquake Res. Inst., Tokyo, v. 3, pp. 1-18, 1927.

Field Research Laboratories,
Magnolia Petroleum Co.,
Dallas, Texas

(Manuscript received May 17, 1951; presented at the Thirty-Second Annual Meeting, Washington, D. C., May 1, 1951; open for formal discussion until May 1, 1952.)

Transactions, American Geophysical Union Volume 32, Number 6 December 1951

INSTRUMENTATION FOR RECORDING MICROCLIMATOLOGICAL FACTORS

F. A. Brooks and C. F. Kelly

Abstract--The objectives, means, and some of the results of intensive studies of the thermal aspects of microclimatological environment are discussed.

The proposed Table 1 of weather types is believed in general to combine rather effectively the European classification, depending on air mass, and the American description by cloud cover. The latter is the more specific for insolation, but the former is most significant for nocturnal heat rates, for moisture, and for air "quality."

The special instrumentation described has been developed in studies of heat transfer from animals and plants, particularly for measuring conduction and radiation. Such electric sensing elements seem to have use in the overall measurement of agricultural climatic environment. The recording potentiometers needed for the micro studies made possible the automatic recording of all the regular weather-station observations described. It is hoped that discussion will lead to some general agreement on minimum instrumentation. Any such agreement would encourage the establishment of many more environment stations and constitute an important step from qualitative toward quantitative experiments.

Examples of the usefulness of the instrumentation are described and a heat balance between solar and sky radiation and the ground is discussed. With adequate understanding of heat balance, we believe that agricultural research findings at one station can be extended to other areas of somewhat different climate.

Introduction

Every investigator of environmental or ecological conditions needs a reference framework of current observations of existing weather and air, sky, and soil conditions, into which he can fit his specialized observations. GEIGER's [1950] description of temperature distribution within a stand of grain is only a qualitative work for lack of standard observations of such elements as air and soil temperatures, moisture conditions, wind velocity, and insolation rate. His report of a wind profile in a forest in only a very interesting picture without data of temperatures, heat rates, or gradient wind. In the absence of convenient environmental data, much agricultural research work has only local applicability. Expensive replicate trials are demanded, therefore, in other localities, and we cannot yet show convincingly how to transfer findings even within a moderate range of climate. The usual thermograph trace is very revealing to an expert, but it records only one of five major factors needed for thermal interpretation of agricultural climatic environment. The whole weather-environment system is so complex that most scientists have neither enough apparatus nor time to fully record ambient conditions.

Daily weather must be classified and the data systematized to be useful

The gloomy specter in all climatological work is the vast amount of labor required for reducing the data to useful forms. For example, in the orchard-heating investigations conducted recently by the University of California, Agricultural Experiment Station, interpretation of all the findings recorded in 30 nights required more than a year. The rate of accumulating data at air-structure stations, such as those near Austin, Texas [JEHN, 1948], and at Brookhaven, New York [LUDLUM, 1948], is staggering, even to seemingly well-manned staffs. At agricultural research stations, where the weather observations may be adequate, the scientist himself usually has to select weather data for his project from original graphical records. This requires so much of his time that he often skips over it and avoids making a specific description, using instead some vague statement of the weather such as: "On a typical warm, clear day . . ." If the climatic interpretations of agricultural research are to be quantitative, it is imperative that all field research be related to the temperature, moisture, and heat observations recorded at standard-exposure stations. For local phenological comparisons, the punching of all data on IBM cards practically eliminates the drudgery in using hourly weather data. Once all observations are on cards, any conceivable correlation can be run very quickly and accurately. But correlations with all kinds of weather jumbled together would not yield very significant results, and such mixtures may be one explanation of the scant use heretofore made of weather data to define test conditions. For reliability of interpretation, it is essential that some guide to weather type be used to insure that only days of reasonable likeness will be grouped together.

Designation of weather type--Meteorologists think of weather type in terms of characteristic air mass and a recognizable pattern of pressure distribution. The cooperative observers who furnish the major information on agricultural climate classified weather until July 1948 as clear, partly cloudy, and cloudy. Neither of these systems is adequate alone for designating comparable days, but sky cover and air mass together should serve rather well. Radiosonde observations provide the most objective way to determine the air mass. For essential simplicity only two air-mass measurements, obtained from radiosonde data, need to be used to describe weather type. These are the temperature at 850 millibars and the precipitable water, recently suggested in a personal communication to the authors by A. K. Showalter of the U. S. Weather Bureau. In the absence of upper-air soundings, the surface observations most nearly approaching these are the temperature and humidity at 14h 00m LCT. These might be supported by net radiation observations at noon and 04h 00m to show degree of cloudiness and also to indicate the precipitable water. Other weather factors, such as wind, usually are also significant. Thus, with the use of a few measurements of surface conditions, it should be possible to estimate air mass and classify the daily weather into at least five types, each more specific than clear, partly cloudy, and cloudy. With such weather types coded onto punch cards, the sorting of the daily records could be done by machine. If meteorologists could be persuaded to classify the daily weather type more specifically, the U. S. Weather Bureau might issue this information, which would permit standardized description either in several narrow or a few broad categories. The hourly records then would contain all the information needed for a great selection of diurnal curves grouped by season and weather type.

Since such coding is not available from the Weather Bureau, we need to consider sunshine, wind, moisture, and temperature as the significant surface factors to classify local weather into a few distinctive types. Considering sunshine and humidity in terms of cloud-cover and air-mass quality, C. F. BROOKS [1949] considers cloudiness in the lower and middle levels most significant and suggests in Table 1 of the present paper how their occurrence in the typical diurnal cycle indicates the probable air mass in non-coastal areas of continental United States. This classification of weather types was suggested by C. F. and F. A. Brooks (revised October 31, 1950). To an expert, the irregular shapes of the daily thermograph traces reveal the effect of cloudiness, wind, and moisture, but for general guidance the approximate diurnal ranges of temperature are included for each proposed weather type. This additional factor helps both to estimate existing type and to visualize the typical diurnal cycles for a given weather type. Noontime wet-bulb depression and also the excess of black globe above dry bulb have characteristic magnitudes for each weather type, but not enough information is available yet to suggest how to use the latter. The two instrumental indicators are rated in per cent relative to monthly mean magnitudes to minimize the large differences between various geographic regions.

Selection of instruments for recording microclimatological factors of agricultural environments

In general, the methods of recording microclimatological environment factors described here were developed for two purposes: (1) to study the effectiveness of various frost-protection methods in orchards; and, at the other extreme, (2) to investigate a means of modifying a hot climate to provide suitable summer environment for displaced livestock. The first difference from usual weather-station instrumentation is the inclusion of soil temperatures, considered here a specific indicator of local climate. It is true that air temperatures in the daytime are practically the same over a single region, but the soil is the major storage for heat, and (excepting times of rapid day-to-day changes) the mean 24-hour temperature must be the level at which there is equilibrium between total heat intake and total discharge. Locally, the insolation and the evaporation cooling will both vary greatly with slope and shielding, and also the heat transfer between ground and air will vary with nocturnal air drift. That these three heat flows at the ground strongly influence the spot climate independently of air temperature is strikingly illustrated by the conditions on the north and south sides of a barn. The daytime air temperatures may be nearly the same in both places, but some plants can grow well on the north side but not on the south and vice versa. Animals and poultry will usually have a preference. They thus select a combination of factors that can be judged most simply by the balance indicated by the soil temperature. Therefore, the soil temperature (on successive similar days) seems to be nature's simplest local indicator of the combined effects of air temperature, convection, radiation, and evapo-condensation. Soil temperature also has direct significance among other things for germination of seeds and activity of soil pests, and should be observed regularly in addition to air temperature.

Minimum instrumentation for reliable interpretation of agricultural environment--The minimum list of factors necessary to define climatic suitability for various plants cannot be stated explicitly. It is significant, however, that NUTTONSON [1946], in his remarkable studies of climatic analogues, found that the only generally available climatic information consisted of the mean

Table 1--Approximate classification of weather type for continental United States suitable for selecting similar days in season

Designation		Visual indicators		Usual air-mass interpretation				Instrumental indication	
Weather category (middle or low levels)	Wea. type[a]	Sky cover (middle and low) average morning and noon tenths	Diurnal cloud cycle or weather	International cloud code[b] CM, mid. level CL, low level	Typical air mass or weather	Air-mass condition: k, colder than ground w, warmer than ground s, stable aloft u, unstable aloft		Diurnal range of dry-bulb temperature in pct of monthly average	Wet-bulb depression 13h or 14h
						Winter	Summer		
Clear or scattered clouds	0	0-2	Day: not windy, usually cloudless Night: cloudless, no fog	MO, or LO	Continental Polar	Colder cPks	Colder cPku	110-130	Large
	1	0-3	Day: windy Morning: usually Cu Noon: usually clear Night: no fog	MO, or L1, or M3, 4	Continental Polar	Colder cPku	Colder cPku	80-105	Average
	2	0-4	Morning: usually Cu Noon: usually clear Night: tendency to fog	MO, 3, 4, 6 L1, 2, 4, 8	Continental Tropical	Warmer cTws	Warmer cTws	110-140	Above average
Partly cloudy	3	3-5	Day: Cu and/or Sc Afternoon: showers Night: usually clearing, no fog	MO, 3, 4, 6 L1, 4, 2, 8	Maritime Polar	Warmer mPws	Colder mPku	80-110	Average
	4	5-8	Day: usually ptly cloudy Afternoon: showers Night: usually clear, no fog	M8, 3, 4, 5, 7, 9 L8, 1, 2, 3, 4, 5	Maritime Tropical	Warmer mTwu	Colder mTku	60-100	Below average
Largely cloudy or overcast	5	6-10	Mostly cloudy or overcast in middle or low levels, without rain or wind as in 7 and 8	M1, 7, 2, 5, 8, 9 L1, 5, 6	Mixed or indifferent Front approaching	Warmer Xws	Warmer Xwu	40-70	Moderately small
	6	8-10	Persistent rain without windshift or destruction as in 8	M2, 1, 7 L7	Pre-warm-front-rain	....	....	20-50	Very small
	7	6-10	Windshift (cold front) usually with downpour	L9, 2, 3	Cold-front-rain	....	....	30-80	Variable
	8	6-10	Destructive wind	L7, 5, 8, 9	Gale, hurricane, violent squall, or tornado	....	....	30-80	Very small

[a]Code number to be punched on IBM card (see Table 3).

[b]U.S. Weather Bureau Circular S, second ed., 1949.

monthly temperatures, total monthly precipitation, and relative humidity. The basic influence of soil temperature could be estimated only in terms of latitude, altitude, and air-mass travel. The most serious lack was observations of transpiration rates. For this, he calculated Thornthwaite's evaporation potential. A Livingston atmometer would have afforded direct measurement.

The minimum list of objective climatic factors necessary to define the well-being of livestock is somewhat different from that for plants, because of the primary need for discharging metabolic heat and for preserving normal body temperature. To indicate the heat-flow conditions in the environment, a simple combination response instrument seems essential as a substitute for the radiation and wind data available at only a few major stations. ADOLPH [1947] shows that man's physiological response by sweating is a good measure of climate in a hot environment. In such a case, the atmometer would be useful. But since cattle, sheep, hogs, and poultry do not sweat, nor do men and horses in cold weather, another instrument is needed for responding to both radiation and air convection. For this purpose, the black-globe thermometer of BEDFORD and WARREN [1934] seems most useful. This instrument measures the temperature toward which a dry body tends when exposed to both radiation and convection. This reading could be used with wet-bulb temperature to describe the livestock comfort zone better than the usual coordinates of dry bulb and wet bulb used in human comfort. The important advantage of the black-globe temperature is that it includes the radiation and convection heat transfers, highly effective and variable outdoors, which are intentionally eliminated from "air temperature."

For measuring heat flow, the first need is for observations of radiation. The simplest measure is by the black-globe temperature, which indicates positively an equilibrium between total radiation and total convection. Either can be calculated if the temperature departure and air velocity at the sphere are known. Even though a kata-thermometer measures heat flow at body temperature, the globe thermometer seems better for a research station, because:

(a) The large globe responds more to radiation, while the small-bulb kata-thermometer emphasizes convective cooling.

(b) The black-globe temperature has some meaning of its own, as does wet bulb. C. O. Mackey of Cornell (Sol-Air inventor) calls this the comfort temperature. It shows at once whether any sizable object tends to warm up or cool down.

(c) The globe thermometer does not require preheating and timed readings.

In the California Station experiments, a six-inch copper globe, commonly used in medical work and readily available, has been found practical. Globes ten cm (four inches) in diameter have been used in Europe. KELLY and Others [1949] compared the behavior of globes having sizes from two to ten inches. His published curve shows the expected 19 per cent variation in globe temperature rise above 86°F air, when the globe is placed in the sun, 24° for a six-inch globe and 22° for a four-inch globe.

Another combined response instrument very desirable for moisture interpretation is the Livingston atmometer [BRIGGS and SHANTZ, 1917], which as a direct measure of capillary evaporation indicates the evapotranspiration potential. The atmometer responds to radiation, wind, and vapor-pressure deficit, which, outdoors, are major factors influencing transpiration rates. When averaged over a month, wind appears to be less important in determining evapotranspiration rates than sunshine; thus VEIHMEYER and HENDRICKSON [1936] found that the variation in use of irrigation water depends primarily on the insolation rate. In general, the atmometer indication differs from wet-bulb depression for the same reasons that globe temperature differs from air temperature. Each of the two combination-response elements is a more specific indicator of suitability of climatic environment for livestock and plants than are air temperature and humidity; but measurements of these latter single factors can be safely omitted only when the interrelationships with radiation and wind are known by experience.

Considering the importance of soil temperature and the accepted inclusion of wind and rain measurements, at least seven climatic elements must be observed in order to describe local farm climate adequately and to relate it to the nearby weather-station climatic data. These are also substantially the same elements needed to describe the microclimate within a grain field or a corral, where the agricultural product itself influences the environment. The only essential difference is in heights of the measurements. Minimum lists of elements for both a portable station for grain field or animal environment use and a small fixed local station to describe farm climate are given in Table 2.

Two small portable stations of the first type were constructed and have given satisfactory service in tomato studies and in a cooperative livestock environmental project at El Centro, California. One of these stations is illustrated in Figure 1. It includes a hygrothermograph for

Table 2--Minimum lists of objective climatic factors needed to describe well-being of livestock and plants[a]

No.	Basic item	Observation	Fixed local stations		Portable spot station	
			Height	Observations	Height[b]	Observations
			inch		inch	
1	A	Air temperature (shielded)	60	Max. and min.	20	Continuous
2	B	Wet-bulb temperature (shielded)[c]	60	Maximum	20	Continuous
3	C	Black-globe temperature (6-in. diam.)	80	Max. and min.	20	Continuous
4	F	Soil temperature	-4	Max. and min.	-4[d]	Continuous
5	M	Wind velocity, hourly mean	80	05h, 13h	24	As desired
6	Q	Capillary evaporation (black atmom.)	80	Weekly	20	As desired
7	T	Precipitation, total	40	Weekly	...	Omit

[a]These seven items are directly observable and can be well presented in annual graphs of weekly means and with probable deviations as the records build up year after year. Many-year records of black-sphere temperature and of atmometer evaporation are as yet almost non-existent, but these have great prospective value. The list above is not to be taken as adequate for agricultural research stations because there a more comprehensive and continuous system of climatic observations is needed.

[b]Heights, except soil temperature, to be raised 20 inches for cattle, and the instruments strongly fenced.

[c]Relative humidity recorded in portable spot station, instead of wet bulb.

[d]Or 0.4 inch.

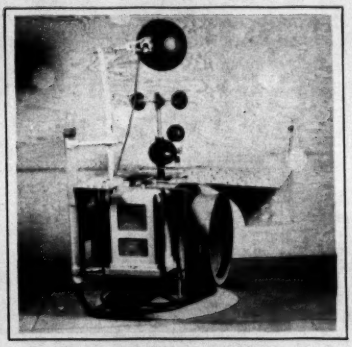


Fig. 1--Portable micro-weather station for use in describing climate at level of plants and animals

recording air temperature and relative humidity, two circular chart thermographs for recording black-globe and ground temperatures, an indicating anemometer, and a black-bulb Livingston atmometer. The difference in heights of thermal elements prevented direct comparison of globe and air temperatures; therefore, the heights listed in Table 2 for dry bulb, wet bulb, and black globe are for the revised design.

Two of the portable stations were used in the summer of 1950 at El Centro to determine how greatly a large shade would modify the micro-environment for cattle. One station was placed in the shade and was moved frequently so that it was always close to the center of the shadow. The other station was left in the sun. At night, the shade station was directly under the shelter. A 24-hour record from the two stations is shown in the graph of Figure 2. The shade did not appreciably alter the air temperature, air velocity, or relative humidity. It had a marked effect on the radiation, as measured by both the globe thermometers and the Livingston atmometers. It is interesting to note that at night the globe thermometer in the open indicated an equilibrium temperature lower than either the air temperature or the corresponding globe temperature under the shelter.

The hourly records of such spot-climate stations can well be punched on IBM cards, using the columns suggested in Table 3. The 24 cards per day would then constitute the permanent original observations in easily available form.

Primary object of climatic recording at an agricultural research station--It is not the function of a local climate station to carry out detailed investigations within the test areas where the presence of the animals or the crops investigated modifies the microclimate. It has a positive duty, however, to keep measuring enough conditions under a standardized exposure to provide a continual reference for every significant factor of the microclimate. The minimum number of these factors recorded at such a station could be as low as seven or eight because of the very close re-

Table 3--Suggested basic climate station recording hourly on 16-point potentiometer

Point	Spot station Item	Spot station Height	Basic station Item	Basic station Height	Observation	Potential or source	Calibration channel	Units	Digits	IBM card columns[b]
		inch		m						
1	A	20	A	0.5	Air temperature	Thermocouple	0	°F	AAA.	12, 13, 14
2	..	..	A1	2.0	Air temperature (standard)	Thermocouple	0	°F	AAA.	15, 16, 17
3	B	20	B	2.0	Wet-bulb depression (×2)	T. C. uncompensated	0	°F	oBB.	18, 19, 20
4	C	20	C	2.0	Black-globe temperature	Thermocouple	0	°F	CCC.	21, 22, 23
5	..	..	A3	15.0	Air temperature	Thermocouple	0	°F	AAA.	24, 25, 26
6	E	-4[c]	E	-0.01	Soil-surface temperature	Thermocouple	0	°F	EEE.	27, 28, 29
7a	..	..	E1	-0.1	Soil temperature	Thermocouple	0	°F	EEE.	30, 31, 32
7b	..	..	E2	-0.5	Soil temperature (root zone)	Thermocouple	0	°F	EEE.	33, 34, 35
8	..	..	G	2.0	Net exchange radiation	Thermopile, cumul.	0[a]	B/hr ft^2	GGG.	39, 40, 41
9	..	..	H	-0.01	Soil heat flow	Thermopile	I	B/hr ft^2	HHH.	42, 43, 44
10	M	24	M1	2.0	Wind velocity	Photocell step emf	0[a]	mph	MMM.	45, 46, 47
11	..	..	M2	15.0	Wind velocity	Photocell step emf	0[a]	mph	MM.	48, 49
12	N	..	N	4.0	Wind direction	356° resistor emf	0[a]	10°	NN.	50, 51
13a	..	..	P	4.0	Turb. (eddy diffusion)	Photocell step emf	0[a]	non-dim.	.PPP	52, 53, 54
13b	Q	20	Q	2.0	Atmometer (capil. evap.)	Micro. pot. res. emf	0[a]	ml/hr	QQ.	55, 56
14a	..	..	R	0.0	Pan evap. (open water)	Tip. bucket step emf	0[a]	in/hr	.oRR	57, 58
14b	..	..	S	-0.1	Soil moisture	Heated thermopile	II	pct	SS.	59, 60
15	T	20	T	1.0	Precipitation	Tip. bucket step emf	0[a]	in/hr	T.TT	61, 62, 63
16a	..	..	..	...	Standardized emf	External battery	0	mv	.....	.....
16b	..	..	..	...	Recorder zero	Short circuit	0	mv	.....	.....
Separate			AB	1.5	Air temp. and rel. humidity	Mechanical	..	°F, pct	Hygro-thermograph	
			F	...	Eppley pyrheliometer	Thermopile	..	cal/hr cm^2	FFF.	36, 37, 38
Nearest hourly-reporting airport					Barometric pressure	Barom. WBAN[d] no. 1 - cols. 33-35				64, 65, 66
					Airport air temperature	Therm. WBAN[d] no. 1 - cols. 47-49				67, 68, 69
					Total cloud cover	Eye WBAN[d] no. 1 - col. 56				70
					Low cloud amount	Eye WBAN[d] no. 1 - col. 57				71
					Cloud type (fog to Cs)	Eye WBAN[d] no. 1 - col. 58				72
					Snow fall (six-hr)	Gage WBAN[d] no. 2 - cols. 19-21				73, 74, 75
					Snow depth	Gage WBAN[d] no. 2 - cols. 22-24				76, 77, 78
					Air mass	Daily weather map				79
					Weather type	Derived, see Table 1				80

[a]Scale adjustable from standardized emf.

[b]Columns 1 to 10 for identification: Place 1, 2, 3; Year 4, 5; Month 6 (with 0-October; 11-November; 12-December); Day 7, 8; 24 Hours 9, 10, 11. Hours could be single column like alphabet; then column 10 could be tenth hours, if column 11 is needed for something else. Where necessary, use hole 11 to designate minus.

[c]Or 0.4 inch.

[d]WB = Weather Bureau, A = Air Force, N = Navy, card-punching; see ref. U.S. Weather Bureau [1948-49].

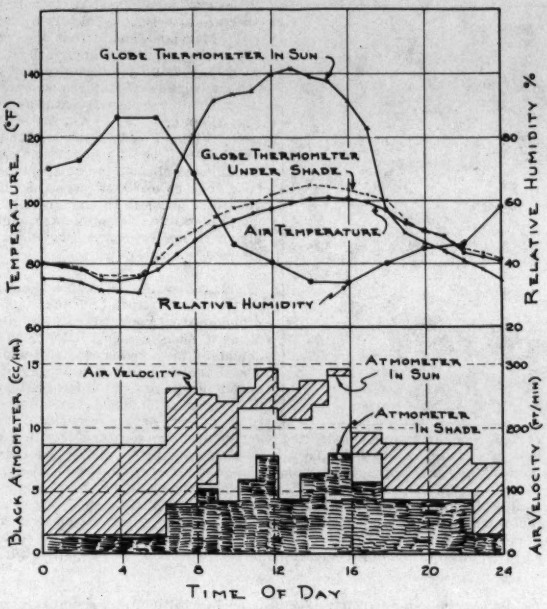


Fig. 2--Micro-environment under cattle shade at El Centro, California, as compared with conditions in open

lationships of all temperatures and all moistures.

At a research station, however, more factors should be recorded continually so that almost direct correlation could be made with whatever micro-environmental factor the agricultural specialist desired to measure. Enough observations should be made so that the dependent relations between them hourly will demonstrate the reliability of the entire set. Then, in case of the failure of one instrument, it will be possible to calculate missing data from the contributing factors shown by other instruments. Furthermore, the research climate-station observations must be adequate for comparing (1) local conditions at various dates, (2) local conditions with climates indicated by Weather Bureau data at other locations, and (3) station conditions with cooperative farm temperature recordings.

Intensive analysis of agricultural research requires a more detailed knowledge of climatic factors than usual observations supply. In general, hourly magnitudes of many climatic factors for standard exposures are necessary for each phenomenon studied in the field. For instance, several groups of agriculturists need to know temperature and moisture profiles from deep in the soil to well above ground. The soil temperatures at 4-, 20-, and 80-inch depths suit most of the needs of agronomists, horticulturists, and engineers. Air-temperature observations at 40 or 80 inches and at 40 feet above ground show the ambient air condition and also nocturnal temperature inversion for cold-air drift and the hazard of radiation frosts. Wind profiles and gustiness are of special interest to engineers, entomologists, and plant pathologists. Measurements of radiation and heat flow and moisture transfer are essential to everyone studying the heat balance of livestock, poultry, and human beings, or the thermal responses of plants.

List of climatic factors suitable for recording with one automatic 16-point potentiometer--

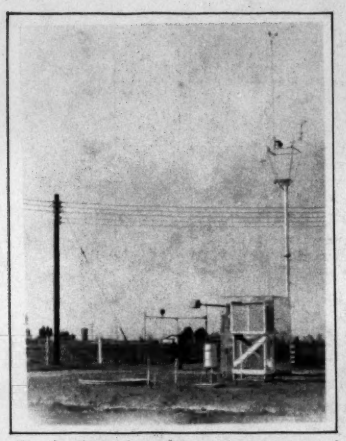


Fig. 3--View of weather station constructed by University of California at Imperial Valley Field Station, El Centro, California

From extensive consultations with agricultural specialists at Davis, California, and at Beltsville, Maryland, and further discussions with climatologists at Washington, D. C., and at Harvard University, the measurement of 28 weather and environmental factors was agreed upon for the agricultural research climate station (see Fig. 3) set up at the University of California Imperial Valley Field Station in 1948 [BROOKS, 1948]. Upon recent reconsideration, the number of elements planned for continual recording has been reduced to 20, as shown in Table 3. If the recording needs to be made by a 16-point automatic electronic potentiometer, eight of the 20 elements can be recorded every two hours (four alternates hourly).

The 20-point list, Table 3, naturally includes all the seven factors of Table 2 (cols. 2 and 3) to provide direct comparison with field microclimatic measurements. Column 5 gives the heights of the sensing elements above ground. These are in metric units largely suiting the recommendations of the International Meteorological Organization. Since scientists in different fields of work naturally prefer various heights and depths, five temperatures in addition to those matching the micro-station are listed to obtain soil- and air-temperature profiles. These indicate air temperatures at any height and soil temperatures at all depths, since deeper temperatures have a known relation to that at moderate depth. The air-temperature profile in conjunction with velocity profile is significant for vertical heat and moisture transport by eddy diffusion, but evaluation needs some measure of air shear stress. This is approached by an observation of turbulence using the oscillation of a sensitive wind vane (item P of Table 3).

The black-plate radiometer [GIER, DUNKLE, and POSSNER, 1949] specifically measures whole-spectrum net radiation, including sunshine and diffuse sky (short-wave) radiation, and atmospheric (long-wave) radiation. Since the plate is exposed to forced air motion, its temperature is close to air temperature, and the net radiation directly observed is itself very nearly what an exposed leaf surface experiences. The response is negative at night, while the usual Eppley glass-covered pyrheliometer shows a zero reading. Absolute, half-space radiation can be calculated by allowing for the outgoing radiation at ground temperature.

Direct measurements of heat flow into and out of the ground are of interest in potato and other storage structures, as well as in frost protection. The heat-flow meter is the same element as used in the black-plate radiometer, except for 25 perforations to prevent undue interference with the moisture distribution under it. This plate meter has to be buried slightly below the soil surface to avoid readings that are false because of momentary contact with air eddies of irregular temperature. A small correction for the heat loss or gain in the one-cm layer above the plate can be made by estimating the thermal capacity of this surface layer.

Soil moisture may be measured by its effect on the thermal conductivity and diffusivity of a porous block. The system employs a heat pulse and determines the temperature rise for a specific time interval [JOHNSTON, 1942]. A two-hour wait between tests is considered essential to avoid a false condition due to artificial drying, which tends to vitiate such findings as those made by a 30-minute cycle technique [ALBRECHT, 1949].

Wind velocity can be recorded electrically by using either the cup anemometer to operate reset step relays to advance a potentiometer resistor, or a heated thermocouple anemometer. By careful design to suppress heat flow axially along the thermocouple wires, the response of this rod anemometer can be made to approach the square root of the air velocity. There is reasonable prospect, therefore, of getting a nearly linear response by interposing an I^2R meter.

An alternative recording every two hours on point 16a provides a verification for the automatic

temperature compensation and the base voltage for the soil-moisture heat pulse and all the step-relay emfs. If this is followed with an alternative recording on point 16b of recorder zero, there is established a standard response pair which also can verify tabulation alignment and timing.

To carry through any power interruption, a mechanical hygro-thermograph is part of the installation. This instrument also serves for direct comparison with observations by farm cooperators. The catch cylinder of the tipping-bucket rain gage preserves the rainfall record during power interruption.

Automatic recording of hourly environmental data

Almost all climatic factors not only are irregular by the minute but also have a strong diurnal cycle. In a qualitative sense, a graphic curve of daily air temperature shows the kind of day at a glance. Quantitatively, it is useless until transcribed and tabulated in numerical digits. It is the quantitative record we need for specific description of environmental conditions. Since it is much too tedious to read continuous graphic traces of sensitive elements to the minute, common practice has centered on hourly observations, as is standard procedure at major airports and in the U. S. Weather Bureau's IBM punch-card climatological system [U. S. WEATHER BUREAU, 1948].

The temperatures recorded should be "on-the-hour" mean magnitudes, smoothing out random momentary variations by using heavy-wire thermocouples, mounted as vertical rods and painted white to minimize radiation errors. Cumulative magnitudes for the whole hour may be preferred for the more irregular factors, such as evaporation and precipitation, and these readings should be treated as "on-the-half-hour." Although it is recognized that automatic, fixed-time recordings do not give the exact maximum and minimum daily temperatures, experience should lead to reliable interpolation of those cases where the scientist desires a closer basis for correlating with the usual maximum-minimum registering thermometers (which are used in the field to measure the diurnal cycle with only one reading per day). However, even for frost damage, it is not the momentary minimum that is significant but the duration of subfreezing temperatures. This again is commonly listed in hours. Agricultural scientists therefore do not seek instantaneous magnitudes but hourly mean magnitudes, possibly sharpened with two maximums within the hour--one of maximum (or extreme) wind, the other of maximum rainfall rate.

With curve-drawing recorders, the cyclic forms of only two or three elements can be seen effectively on one chart; but for purely quantitative recording, 16 or 20 elements can be recorded clearly on a single potentiometer recorder. So our intention for the past few years was to convert a regular 16-point electronic potentiometer strip-chart recorder to shift a type-faced counter (driven by the slide-wire drum) electrically to print in 16 columns. Because of insufficient space for the ink-tape mechanism inside the regular instrument housing, this was not accomplished. In 1949, however, a separate industrial counter-printer was geared to the slidewire drive so as to record emfs to 0.1 per cent of full scale in three digits. Although each of the emfs printed is labelled with its circuit number, the very fact that all appear in a single column renders the strip record almost unintelligible to anyone not active on its interpretation. The printing in digits has saved very tedious work deciphering the previous graphical chart, but to be really useful to all agricultural scientists, it is obviously necessary to get these digits tabulated in 16 or 20 respective columns. The same printing problem for fast electronic potentiometers was solved this year for the aircraft industry by applying triple decade switches which operate an electric typewriter through 12 wires [BENSON - LEHNER CORP., 1950]. This is used in rapid automatic calculation, and tabulation is easily accomplished. Even an additional connection for automatic punching of IBM cards is part of this fast apparatus. This industrial accomplishment, therefore, seems to warrant immediate application to the recording of hourly weather data. At Davis a relocated weather station has been authorized using the all-electric system of Table 3 with manually adjustable scale-range controls on the non-temperature items. Each item automatically tabulated will appear in ordinary units according to the calibration of the sensing element (cols. 9, 10 of Table 3). It now seems that English units -40 to +200 for maximum scale will be used to provide direct reading for insolation rate in Btu/hr ft^2. Temperatures in whole degree F would then use only half the potentiometer range, but closer recording is unnecessary.

Automatic weather station--The all-electric system of hourly recording described above permits establishment of comprehensive automatic weather stations with little additional manpower. Such a development would be very valuable in agricultural regions not on important airways, which are not now served because the three- or four-man crew needed for each conventional station is too expensive. More limited automatic weather stations have already been developed, such as the remote radio-reporting weather station of the Harvard Blue Hill Meteorological Observatory and that of the Bendix Corporation, using self-starting, engine-driven packaged

apparatus. Both of these installations with their extra radio starting and sending apparatus are more subject to failure than the in-station recording by the industrial automatic potentiometer assembly proposed above. In the future, with telemetering by six wires, city-office tabulation of outside airport observations should be practicable.

When one considers the extensive industrial use of mechanical counters, electric meters, recording potentiometers, and automatic telephone exchanges on continual duty year after year, there seems little reason for not achieving a climate-recording station that requires servicing only once a week. The output of this station could include an hourly tabulation of 20 elements (col. 6, Table 3) and one IBM card per hour (last col., Table 3). The exclusion of all non-instrumental observations, however, constitutes an important limitation of absentee operators. Cloudiness in the sense of energy interference is measured by the radiation instruments; but for fog and thunderstorms, snow and hail, supplementary information should be obtained from the nearest Weather Bureau station. If a major airport is nearby, their hourly observations of these supplementary meteorological factors might well be punched in the unused columns of the local climatological station IBM cards. As indicated at the bottom of Table 3, the desirable WBAN items seem to be: air temperature (for relating local station to airport), clouds, and snow. It is to be regretted that no entries are available for air mass and some index of weather type or the time-position relative to cyclonic structure.

Estimation of heat balance from hourly microclimatological observations

A livestock environmental project, undertaken at El Centro and at Davis, had as its purpose the development of means to modify the climate by structures, plantings, or other media, and thus to promote more economical growth and greater comfort of livestock. Climatic factors, especially those related to solar and sky radiation, were measured. In order to transfer the findings regarding livestock shade to areas having climates different from El Centro or Davis, it should be possible to predict the amounts of radiant energy to be expected from the ground without resorting to more than a knowledge of the local total upper hemisphere radiation and typical ground temperatures. This could be done if the reflectivity of the ground for solar radiation and the emissivity of the ground at its usual temperatures were known. Simultaneous microclimatic records of solar and sky radiation, ground radiation, air temperatures and velocities, and ground temperatures, to supplement the records from the University weather stations at the two locations, were collected for several days with the best instruments available.

Relative importance of upper and lower hemisphere radiation--A livestock shade is designed to give the maximum shielding of the animal from both solar and ground radiation. The importance of the lower hemisphere radiation from the ground should not be underestimated; the measurements show (and it can be calculated) that the radiant energy falling on an animal the size of a cow, which stands at the center of the shadow under a typical shade, will be at least as much from the lower hemisphere as from the upper. For animals closer to the ground, such as swine and poultry, the lower hemisphere radiation becomes less important, but it still amounts to almost half of the total. The ground radiation includes both the "self radiosity" or long-wave emission from the surface, which can be calculated if the ground temperature and emissivity are known, and the short-wave solar energy, which is reflected by the ground. Both of these factors depend directly or indirectly upon the amount of energy reaching the Earth from the Sun.

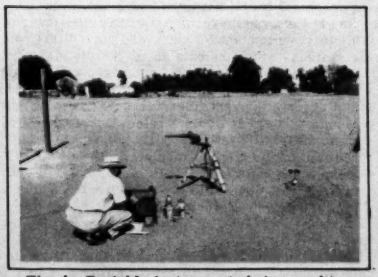


Fig. 4--Portable instruments being used to measure solar and sky radiation, ground temperature, energy absorbed by the ground and air velocity; general-purpose directional radiometer, for measuring total energy emitted by ground, not shown

Heat balance between incoming radiation and the ground--With the portable instruments used on the livestock environmental project, it was possible to measure the energy reaching the Earth from the Sun and sky and also to partition this energy into the various channels it follows after reaching the Earth, if the heat lost through evaporation is included in the convection losses. A view of the portable radiation station is shown in Figure 4, and the use and calibration of the instruments is discussed by KELLY and Others [1949]. At both El Centro and Davis, the ground

Table 4--Disposition of solar energy and its measurement

Item	Channel	Instruments involved	Symbol
1	Total solar and sky radiation	Black plate, whole spectrum, hemispherical, radiometer	G
2	Net heat absorbed by ground	Heat-flow meter, 2 inches square	E_a
3	Emissive power of ground	Touch thermocouple to measure ground-surface temperature	E_e
4	Heat reflected by ground	Directional Gier radiometer	E_r
5	Heat lost through convection	Anemometer	E_c

was baked and dry, having received neither rain nor irrigation water for months preceding; as a result, the soil evaporation loss must have been very small.

Table 4 indicates (1) the various channels into which flows the solar energy reaching the Earth, and (2) the instruments used for the measurements in these investigations.

The directional radiometer mentioned under item 4 measures the total radiosity of the ground, of course, rather than just the fraction reflected [GIER and BOELTER, 1941].

It is evident that the incident heat rate G should be equal to the sum of the heat flows away from the surface, $E_a + E_e + E_r + E_c$. The best check one could have on the instrumental observations would be a satisfaction of this equation. Unfortunately, E_r and E_c cannot yet be measured directly, but the results from the described method are encouraging, when the E_c found by subtraction indicates a reasonable value for the surface film coefficient for convection.

A start has been made in developing the heat balance necessary to calculate the ground reflectivity at El Centro and Davis, assuming an emissivity for the ground of 0.90. The following discussion will describe step by step the method followed, using El Centro data.

(1) Measurements were made of the total solar and sky radiation by means of the black-plate radiometer; of the total radiation from the ground, including both reflected and radiated energy,

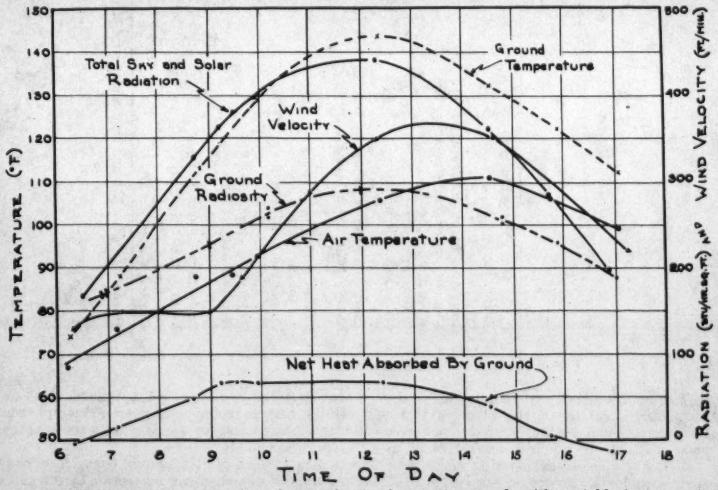


Fig. 5--Temperature, radiation, and air-velocity observations made with portable instruments at El Centro, California, on August 18, 1949; ground radiosity determined by two Gier radiometers directed, respectively, 30° below the north and south horizons; negative values of net heat absorption by the ground indicates a net loss of heat.

Table 5--Hourly observations of radiation and climatic factors interpolated from curves of Figure 5, and results of heat-balance calculation

Line	Item	Time											
		7h	8h	9h	10h	11h	12h	13h	14h	15h	16h	17h	
1	Upper hemisphere radiation (Btu/hr sq ft)	205	275	350	402	432	440	426	387	334	260	288	
2	Air temperature (°F)	74	81	87	93	99	104	107	111	110	104	99.5	
3	Ground surface temperature (°F)	85	101	115	129	140	144	143	137	129	121	113	
4	Radiosity of ground (Btu/hr sq ft)	172	200	225	258	282	290	288	275	252	224	188	
5	Net heat absorbed by ground (Btu/hr sq ft)	13	36	60	68	68	68	62	47	24	0	-20	
6	Air velocity (ft/min)	145	150	150	220	285	336	360	362	330	280	230	
7	Energy emitted by ground (ϵ = 0.90)	137	154	170	187	201	206	203	198	187	178	167.5	
8	Energy reflected by ground (Btu/hr sq ft)	35	46	55	71	81	84	85	77	65	46	20.5	
9	Radiosity plus net absorption (Btu/hr sq ft)	185	236	285	326	250	358	350	322	276	224	178	
10	Convection loss (Btu/hr sq ft)	20	39	65	76	82	82	76	65	58	36	20	
11	Δt (°F)	11	20	28	36	41	40	36	26	19	17	13.5	
12	Surface film coefficient (Btu/hr sq ft) (°F)	1.82	1.95	2.32	2.11	2.00	2.05	2.11	2.5	3.05	2.12	1.48	
13	Convection E_c (pct)	9.75	14.2	18.6	18.9	19.0	18.6	17.8	16.8	17.4	13.8	9.62[a]	
14	Absorbed, net E_a (pct)	6.35	13.1	17.1	16.9	15.7	15.4	14.6	12.1	7.2	0		
15	Reflected E_r (pct)	17.1	16.7	15.7	17.6	18.7	19.1	19.9	19.9	19.5	17.7	9.85	
16	Emitted E_e (pct)	67.0	56.0	48.5	46.5	46.5	46.8	47.7	51.2	56.0	68.4	80.5	

[a]Percentages for 17h are fraction of sum of solar and sky radiation and ground heat.

by means of a directional radiometer; of the net heat absorbed by the ground, by means of a two-inch square heat-flow meter placed 1/16 inch under the surface of the soil; of ground temperature by a touch thermocouple; of air temperature one foot above ground, by a shielded thermocouple; and of air velocity one foot above ground, by a Cassela anemometer.

(2) A graph was prepared in which the climatic factors were plotted against time. The measurements for El Centro on August 18, 1949, for the time of day when net absorption by the ground was positive, are presented in Figure 5. The ground temperatures in each case are the average of five observations. Plotting is necessary to provide a convenient method of interpolating, since the hourly observations by the manually-operated indicating instruments could not all be made at the same instant.

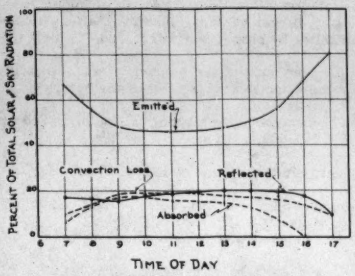


Fig. 6--Per cent of total incoming solar and sky radiation reflected, absorbed, lost by convection, and radiated back to sky, as found in study at El Centro, California, August 18, 1949

(3) From the curves of Figure 5, values for the several factors were read at one-hour intervals for the period 7h 00m to 17h 00m. These are recorded in Table 5 (lines 1 to 6 inclusive). The rate of heat flow through the various channels could then be estimated.

(4) The long-wave emission from the ground E_e, recorded as line 7 in Table 5, was calculated by the Stefan-Boltzmann formula, using the ground temperature (line 3) as the radiating temperature and assuming an emissivity for the ground of 0.90. The total radiant energy reflected by the ground (E_r) is equal to the total radiosity of the ground as measured by the directional radiometer (line 4) minus the emissive power of the ground surface (E_e, line 7). E_r is recorded as line 8. This reflected energy has little relation to the assumed long-wave reflectivity (ten per cent), because reflected solar energy is in the short-wave region. The convection and evaporation loss (E_c) was equal to the total incoming radiation (G, line 1) minus the sum of the absorbed, emitted, and reflected energies ($E_a + E_e + E_r$). This sum, line 9, was determined by adding the values in lines 4 and 5. The convection loss (E_c) for each hour is recorded in line 10.

(5) The surface film coefficient h_c was found by formula $h_c = q_c/\Delta t$, where q_c is the rate of heat loss by convection (line 10) and Δt is the difference between ground temperature and air temperature (line 11). The surface film coefficient for each hour is recorded in line 12.

(6) The percentage of the total incoming radiation represented by each channel of heat transfer was found by dividing the values for the individual channels by the value for incoming radiation (line 1). These percentages are shown in lines 13 to 16 and are plotted in the graph of Figure 6.

Convection loss--When the convection loss was found by subtraction, the calculated surface film coefficient could then be used to show whether or not the losses were reasonable. Measurements of air velocity and temperature were made only one foot above the ground, somewhat lower than is ordinarily considered representative of the mass of air in convection studies. Furthermore, the observations were made on an area of ground about 150 ft square, flat, but surrounded by haystacks, corrals, and shades; turbulence may have been set up by these objects. A turbulence meter is needed for studies of this type.

Acknowledgments--The development of this instrumentation naturally involves many staff members of the Experiment Station, particularly C. E. Barbee, in charge of the Agricultural Engineering Research Laboratory. We have enjoyed the active cooperation also of the Colleges of Engineering at Berkeley and Los Angeles and generous assistance by the Leeds and Northrup Co., the Brown Instrument Division of the Minneapolis-Honeywell Regulator Co., the Streeter-Amet Co., and Cassela, Ltd., London.

References

ADOLPH, E. F., and ASSOCIATES, Physiology of man in the desert, Interscience Publishers, Inc., New York, pp. 77-78, 1947.

ALBRECHT, F., Die Weiterentwicklung der Messtechnik des Wassergehalts des Bodens auf Thermischer Grundlage, Archiv für Met., Geophys. und Bioklim., Ser. B, v. 1, pp. 149-155, 1949.

BEDFORD and WARREN, The globe thermometer in studies of heating and ventilation, J. of Hygiene, v. 134, p. 458, 1934.

BENSON-LEHNER CORP. (2340 Sawtelle Blvd., Los Angeles 64, Calif.), Gift of tongues; analog-digital converter, Business Week, no. 1096, p. 44, September 2, 1950.

BRIGGS, L. J., and H. L. SHANTZ, Comparison of the hourly evaporation rate of atmometers and free water surfaces with the transpiration rate of Medicago Sativa, J. Agr. Res., v. 9, pp. 277-292, 1917.

BROOKS, C. F., The revised cloud codes CL, CM, and CH, Bull. Amer. Met. Soc., v. 30, pp. 31-33, 1949 (see also Harvard Lecture Notes).

BROOKS, F. A., Outline for comprehensive interpretation of local climate for Calif. Agric., presented at Ninety-Ninth Meeting, Amer. Met. Soc., Berkeley, Calif., June 24, 1948 (unpublished).
GEIGER, RUDOLF, Climate near the ground, translation by Milroy N. Stewart, 2nd ed., Harvard Univ. Press, Cambridge, 1950.
GIER, J. T., and L. M. K. BOELTER, the silver-constantan plated thermopile, in Amer. Inst. of Physics and others, Temperature, its measurement and control in science and industry, pp. 1284-1292, Rheinhold Pub. Corp., 1362 pp., 1941.
GIER, J. T., R. V. DUNKLE, and L. POSSNER, Measurements of hemispherical radiation and net radiation exchange, Report 10, Report Code NR-014-062, contract N7-ONR-295 - Task 1, August 1949.
JEHN, K. H., The experimental micrometeorological field installation at Manor, Texas, Bull. Amer. Met. Soc., v. 29, pp. 357-374, 1948.
JOHNSTON, C. N., Water permeable jacketed thermal radiators as indicators of field capacity and permanent wilting percentage, Soil Sci., v. 54, pp. 123-125, 1942.
KELLY, C. F., T. E. BOND, and C. LORENZEN, JR., Instrumentation for animal-shelter research, Agric. Eng., v. 30, p. 302, 1949.
LUDLUM, D. M., Micrometeorology at Brookhaven, Weatherwise, v. 1, pp. 95-98, 107, 1948.
NUTTONSON, M. Y., Agricultural climatology, physical belts and crop ecology--Palestine vs. U.S.A., Office, Foreign Agricultural Relations, Report 14, U. S. Dept. Agric., September 1946; also in Geogr. Rev., v. 37, pp. 436-456, 1947.
U. S. WEATHER BUREAU, Instructions for WBAN Card Punching, pp. 1-77, July 1948, with revision January 1, 1949.
VEIHMEYER, F. J., and A. H. HENDRICKSON, Essentials of irrigation and cultivation of orchards, University of California, College of Agriculture, Circular 50, 1936.

University of California,
Agricultural Experiment Station, and
U. S. Department of Agriculture,
Davis, California

(Manuscript received March 6, 1950, and, as revised, May 14, 1951; presented at Twenty-Fifth Regional Meeting, Davis, California, February 3, 1950; open for formal discussion May 1, 1952.)

DISCUSSION

Herbert B. Schultz (College of Agriculture, University of California, Davis, Calif.)--In the paper under discussion the objective of the authors is to give a complete plan of activity necessary in microclimatological work. Realizing that agricultural climatology badly needs a day-to-day classification of the actual weather, F. A. Brooks undertook this task, together with Charles F. Brooks, who for a long time has been interested in weather typing, as indicated by his early publications [BROOKS and OTHERS, 1925].

At first glance two things are noteworthy in the Brooks' results. One of these is their close adherence to the well-known air-mass classification. This is another proof of the usefulness of the "air-mass climatology" as introduced by LANDSBERG [1947]. Such an affinity to regular air-mass nomenclature is useful since every meteorologist can easily get acquainted with the authors' weather types. As F. A. Brooks intends to use these types for agriculture, he is especially anxious to classify by sky-cover and weather phenomena. The second noteworthy feature of their work is that F. A. and C. F. Brooks succeeded in condensing two systems of classification into a simple set of only nine types, few enough to be punched in a single column on WBAN cards.

At the College of Agriculture of the University of California at Davis, we now can verify the usefulness of this classification on a large scale by using it for interpreting bioclimatological work on the Oriental Fruit Fly Project. In order to give descriptive information useful to entomologists and other interested scientists, we construct a "weather calendar" containing the pertinent data for the given months. The calendar for January 1950 made with data taken at Riverside, California, is presented herewith as Figure 7. In connection with this example, it is worthwhile mentioning that citrus orchard heating was necessary only when weather type 0 occurred. By using the Brooks' classification, it is now possible to use one term to describe this situation where formerly two factors had to be used, namely, (1) a special air mass (cold and dry), and (2) a clear, calm night. Since the air masses are included, the weather typing makes it possible to compare the results we are getting for the West Coast with other places, especially with LANDSBERG's [1937] findings for the East Coast of the United States.

Table 6--Yearly average of diurnal range of temperature for the various weather types, amounts in per cent of general average

Station	Weather type									Yearly average diurnal range
	0	1	2	3	4	5	6	7	8	
										°F
Camino	125	101	128	85	....	71	40	71	...	20.3
Lindsay	111	88	132	88	100	50	50	45	...	27.5
Yuba City	112	94	138	89	126	64	42	62	...	28.5
Davis	114	81	136	79	127	57	46	34	...	29.2
San Jose	134	84	147	98	....	70	52	63	...	26.9
Sebastopol	132	90	152	100	97	68	47	75	61	27.9

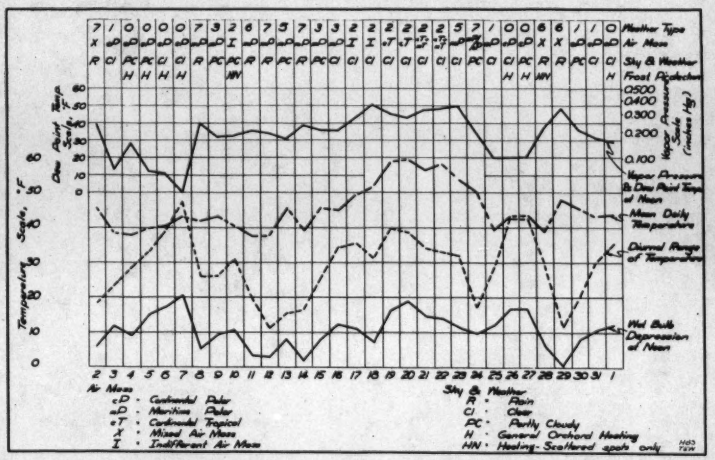


Fig. 7--Weather calendar for Riverside, California, for January 1950

Another interesting item in Table 1 of the paper under discussion is the diurnal range of temperature. It seems to be a good idea to use percentages in order to make the table descriptive, but more important, influences due to local climate and exposure are eliminated. For a rough check, I used the data given in Table 6. These are yearly averages of diurnal temperature range for six California stations between the Sierra foothill area to the West Coast, and the yearly average for every weather type in per cent of the general average. These percentages approximate the figures given by Brooks; however, they do not reveal the wide scatter, so for practical use on a certain day the percentage should be calculated by reference to the monthly average or at least to the seasonal average. The main disadvantage is that the monthly averages are not compounded by the same portions of each weather type. Thus, the spread of percentages given in Brooks' table may not be big enough; for example, in a winter month, there may occur 25 days with a diurnal range of 10°F and five days with one of 30°F. Then the average diurnal range for the month would be 13.3°F. The deviation for the first group would be 10/13.3 = 75 pct, and for the second one 30/13.3 = 231 pct. In the summer, the opposite may be the case. We expect to be able to describe more closely the diurnal ranges for various stations as the actual work proceeds in interpreting day-by-day conditions.

The term "weather types" used by the authors to describe day-by-day conditions should not be confused with the same expression used by long-range forecasters for broad-scale synoptic situations describing typical weather patterns for a week or more and for an area the size of a country.

References

BROOKS, C. F., and OTHERS, Papers on the relation of the atmosphere to human comfort, Mon. Wea. Rev., v. 53, pp. 425-437, 1925.

LANDSBERG, H., Physical climatology, 4th printing, Pennsylvania State College, 1947.

LANDSBERG, H., Air-mass climatology for central Pennsylvania, Beitr. Geophys., v. 51, pp. 278-285, 1937.

Transactions, American Geophysical Union Volume 32, Number 6 December 1951

A KINEMATIC RELATIONSHIP IN THE FIELD OF MOTION IN STORMS

Leon Sherman

Abstract--In this paper a method is suggested for estimating the direction of the basic flow field in the presence of a disturbance in that field. It is reasonable to consider, as a disturbance entity, the pair of singularities consisting of a cyclonic point, cyclonic indraft point, and so forth, and the accompanying hyperbolic point. In most cases for young disturbances a valid estimate of the direction of the embedding current is 180° apart from the value of the isogon directly joining the two singular points of such a disturbance. It is possible to recognize from the map whether or not this rule should apply.

In 1911 two volumes of a work sponsored by the Carnegie Institution of Washington appeared. The first, which included V. Bjerknes' hydrostatic tables, left a lasting imprint upon meteorological practice. Unfortunately the second, concerned with kinematics, has not had a similar effect. In this note we present an example of kinematic reasoning taken from a recent report of the Tropical Pacific Project at the Institute of Geophysics of the University of California. In meteorological literature the basic sources on this subject are a paper by SANDSTRÖM [1909], the volume by BJERKNES and Others [1911], and a paper by WERENSKIOLD [1922]. A treatment from the mathematical viewpoint is given by LEFSCHETZ [1948]. In the following discussion we shall first review some of the terminology associated with streamline analysis, suggest a pattern appropriate for consideration as a disturbance of the field, and finally derive and illustrate a rule by which the direction of the current in which a disturbance is embedded can be deduced from the disturbed field of motion.

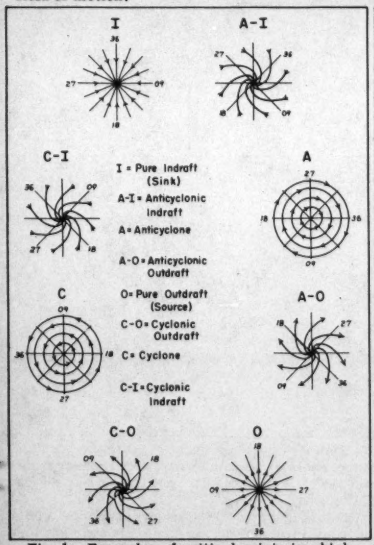


Fig. 1--Examples of critical points in which the isogon value increases in a clockwise sense [after V. BJERKNES, 1911]

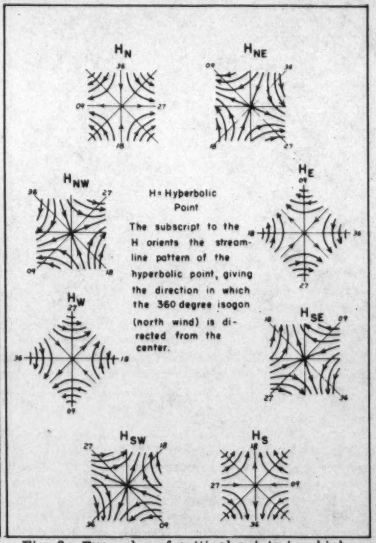

H_N
H_NE
H_NW
H_E
H_W
H_SE
H_SW
H_S
H = Hyperbolic Point
The subscript to the H orients the streamline pattern of the hyperbolic point, giving the direction in which the 360 degree isogon (north wind) is directed from the center.

Fig. 2--Examples of critical points in which the isogon value decreases in a clockwise sense [after V. BJERKNES, 1911]

In practice we can represent the horizontal wind field as regular save for certain simple sorts of critical points. Some of these are illustrated in Figure 1. The cyclone, anticyclone, source, and sink are essentially limiting cases. They are the points which have been most treated in theory. The combinations of these points (such as C-I) are by far of most common occurrence. Indicated in Figure 1 are not only streamlines but some isogons (or lines of common wind direction). For example, in the anticyclonic point (A-I), the wind is everywhere north along the 360° isogon. Notice too, that in these patterns the isogons change their values by 180° upon passing through a critical point. All the points illustrated in this figure have the common property that the numbering of their isogons increases in the clockwise sense. In Figure 2 we have a set of critical points in which the numbering of the isogons decreases clockwise.

We are faced with the difficulty that each of these critical points has the undesirable property that, no matter how far from them we look along any given azimuth, the wind direction continues to be strongly dependent upon the initial choice of azimuth. This difficulty is resolved if we regard as our disturbance entities combinations (such as those in Fig. 3) of the classes of points shown in Figures 1 and 2. These combinations have the property that, with increasing distance from them, the winds approach some common direction. Exact topological reasoning yields the result that, save for a transitional instant when a somewhat more complex singularity appears, from one synoptic map to another the number of singular points of the sort we have shown in Figures 1 and 2 can differ only by an even number. (We also here assume, as in general we may, that only simple critical points enter our maps.) Furthermore, these points will appear or disappear in pairs, each pair consisting of one point from each of the classes shown in Figures 1 and 2. This also makes reasonable the acceptance of these pairs of critical points as our disturbance entities.

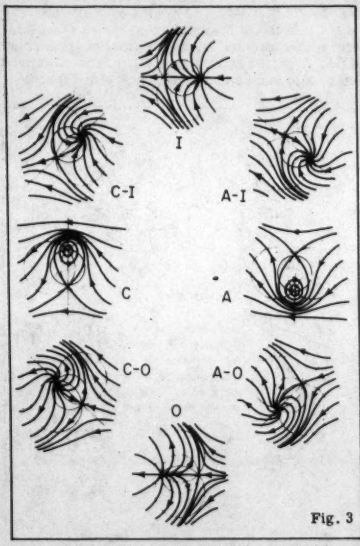


Fig. 3

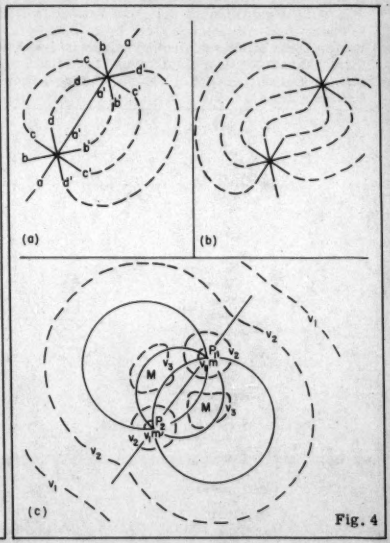


Fig. 4

Fig. 3--Possible simple disturbance entities on an easterly basic current; these are the possible pairings of the points of Figures 1 and 2 on such an easterly basic current; the pairs are named for the points of Figure 1 which entered into each (to obtain the possible patterns for other basic currents it is only necessary to rotate the whole figure)

Fig. 4--Isogon relationships in the disturbance entities of Figure 3; (a) the isogon pattern of a point of Figure 1 joined in a simple way to that of a point of Figure 2; (b) a less simple such juncture which is possible but is not contemplated for the purpose of this paper; (c) a typical disturbance entity: the pattern of (a) formalized (the dashed lines are speed lines showing a minimum of speed at each of the critical points P_1 and P_2)

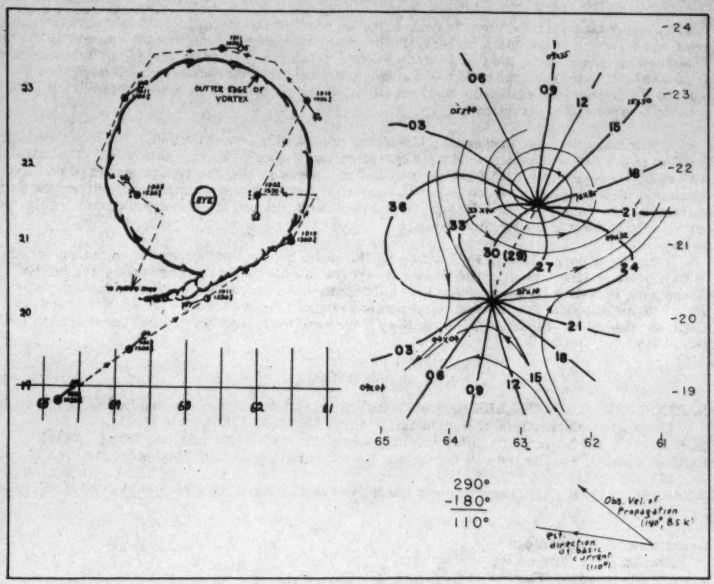


Fig. 5--A synoptic example, hurricane flight of August 26, 1948; on the left is a sketch taken from a U. S. Navy report; on the right the isogon pattern and a few streamlines have been entered; each wind report is entered in the form: dd × vv, in tenths of degrees and knots respectively; small dotted lines show the displacement of the observation required on the basis of the observed storm motion to give an instantaneous pattern

In these pairings, as we have drawn them, the isogons have a characteristic pattern. Its essential feature, repeated in Figure 4, is the pair of critical points from which isogons radiate. In Figure 4a we have simply indicated two such patterns in close proximity, and have joined the isogons of one with those of the other. This construction in itself indicates why the points must be paired each with another of opposite sense of increasing isogon value.

The critical points in Figure 4a are simply joined. We can well imagine a more complex situation such as that illustrated in Figure 4b. However, we shall assume that such a situation occurs only when the critical points are widely separated. Initially the two points will be quite close together, and it is at least plausible that the pattern of Figure 4a will fit. In Figure 4c we have replaced the isogons by circles, so obtaining patterns as in Figure 3. This is unimportant to the argument and was done only to simplify the figures.

As noted above, the isogons change value by 180° upon passing through the critical points of Figures 1 to 3. This is not a logical necessity; however, we shall assume sufficient angular symmetry of isogons near those critical points we consider, so that the change in their value upon straight passage through the point is at least approximately 180°. The isogon represented by the rays extending outward along the line joining the critical points bears the value of the basic current direction, for as we move away in any direction from the disturbance we encounter directions approaching this isogon value. Accordingly, at least for small disturbances (which have a simple isogon pattern) the value of the basic current direction is approximately 180° from that of the isogon joining the critical points. This is the kinematic relationship that we here describe. In Figure 5 is presented a synoptic example taken from the as yet very meager file on an investigation of

hurricane propagation in which it is desired to see whether the storm path deviates systematically from the direction of the basic current. In the case shown, the direction of the embedding current, computed by means of the method described above, turns out to be from 110°; the storm motion from 140°. It is to be emphasized that the kinematic relationship here discussed might equally well be illustrated by a case from the westerlies, or for that matter by a disturbance embedded in a basic current of any direction.

In summary, we have presented a kinematic rule by which the direction of the basic current present in the rather complex wind field of a disturbance may be quickly estimated. That direction differs by approximately 180° from the value of the isogon joining the critical points of the disturbance. Disturbances to which this rule is to apply have two recognizable properties: the critical points must be simply joined (see Fig. 4), and they must possess at least approximate angular symmetry with respect to isogon distribution.

Acknowledgment--This is Publication No. 11 of the Institute of Geophysics of the University of California at Los Angeles. The research reported in this paper has been sponsored by the Geophysics Research Division of Air Force Cambridge Research Center under Contract W28-099 ac-385. The data used in the synoptic example (Fig. 5) are taken from Hurricanes of 1948, an unpublished report of the U. S. Navy Caribbean hurricane reconnaissance flights of 1948, Dec. 1948.

References

BJERKNES, V., TH. HESSELBERG, and O. DEVIK, Dynamic meteorology and hydrography, pt. II: Kinematics, Carnegie Inst. Washington Pub. no. 88, pt. II, 175 pp., 1911.

LEFSCHETZ, S., Lectures on differential equations, Princeton Univ. Press, 209 pp., 1948.

SANDSTRÖM, O. W., Über die Bewegung der Flussigkeiten, Ann. Hydr. und Mar. Met., v. 37, pp. 242-254, 1909.

WERENSKIOLD, W., Air transport over the North Pacific Ocean, Geofys. Publikasjoner, II, pp. 1-55, 1922.

Department of Meteorology,
Florida State University,
Tallahassee, Florida

(Manuscript received March 2, 1951; presented at the Twenty-Sixth Meeting, Fresno, California, February 9, 1951; open for formal discussion until May 1, 1952.)

Transactions, American Geophysical Union Volume 32, Number 6 December 1951

ANALYZING TURBULENCE BY MEANS OF PHOTOGRAPHS OF AIRBORNE PARTICLES

Albert V. Hardy

Abstract--A recently developed technique for obtaining experimental turbulence data by photographing lint particles floating in the air is described, and some of the problems inherent to the method discussed. The sources of error occurring in such data are enumerated, and a mathematical analysis is made to determine the importance of the resultant inaccuracies.

Introduction--Most of the numerous analyses of fluid turbulence made since the publication of REYNOLDS' [1895] basic paper have dealt with the theory. Few experimental studies of the details of turbulent motion have been undertaken, and still fewer show success in observing these details accurately. The need for more experimental data from which to check the postulates involved in the theory is well recognized [HALL and POPPENDIEK, 1949]; the shortage of such data is largely due to technical difficulties involved in measurement. The nature of a fluid is such as to make its movements exceedingly complex, and at the same time to make the details of the movements unobservable without the introduction of some sort of instrumentation. The principal problem in accurately measuring fluid turbulence is to find a means of precisely recording fluid motions without at the same time influencing those motions.

The importance of turbulence in gases is best illustrated in the atmosphere. Air movements are commonly measured by two instruments: one, the anemometer, to measure speeds, and the other, the vane, to measure directions. Of the many types of wind instruments made, only a few are designed to measure the details of turbulent motion. All these have two failings in common: instrumental lag, and instrumental interference with the flow pattern.

MILLER, BADGLEY, and SINGER [1949] have introduced a new photographic method which promises to minimize some of the difficulties encountered in previous experimental studies of atmospheric turbulence. It is the purpose of this paper to examine some of the technical problems involved in the use of this method. A brief description of the technique is in order.

The procedure is to make stereoscopic pairs of photographs of airborne particles floating freely in the field to be studied. This is accomplished by the use of two similar cameras with synchronized shutters, placed with lenses about 30 cm apart and pointed in the same direction. With these cameras focused on the field to be studied, simultaneous exposures of the order of one second are taken. Illumination is supplied by a gas-discharge type of stroboscopic light which gives intense flashes of very short duration, repeated in a predetermined pattern. As each particle moves across the field it is photographed as a series of dots, from which the trajectory can easily be identified. From the pair of photographs thus produced, simple geometry determines the three-dimensional position of each particle at any time during the exposure.

The most fundamental problem in initiating this experiment was the selection of particles that are effectively airborne and at the same time photograph well. Of numerous substances tested, the lint particles that may be rubbed or shaken from Kleenex or similar facial tissues were found most nearly satisfactory. These are extremely sensitive to air movement and photograph very well when strongly lighted. Photomicrographs of representative particles are shown in Figure 1. In spite of the irregular appearance of the particles, their movement in still air is vertically downward at a small, constant speed.

Trajectories have been measured on a number of photographs produced by the technique described, and the data thus obtained are being examined statistically [BADGLEY, 1950; MILLER, 1950]. However, an accurate evaluation of the data cannot be made without first determining to what extent the movement of a lint particle accurately represents the instantaneous value of the air movement. It is evident that the particles, being heavier than air, have some downward movement relative to the air. It is also apparent that inertial effects may prevent the lateral motion of the particles from corresponding exactly to that of the air. An effort has been made to evaluate these sources of discrepancy by the use of special apparatus.

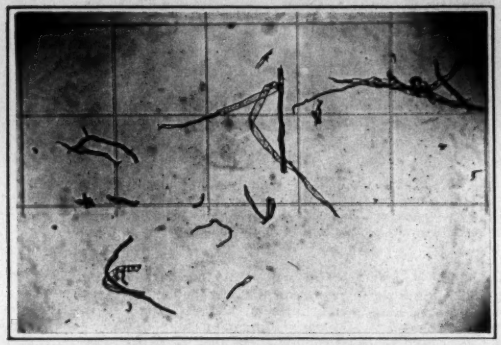


Fig. 1--Photomicrograph of representative Kleenex particles; grid rulings are 1/36 inch apart

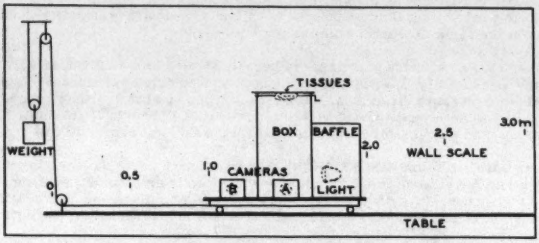


Fig. 2--Acceleration apparatus, side elevation

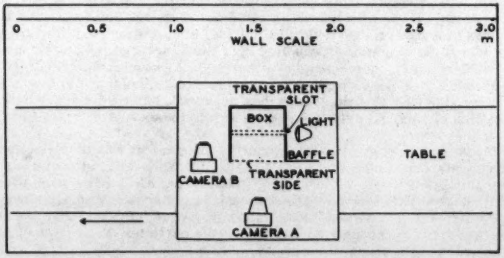


Fig. 3--Acceleration apparatus, horizontal cross section

Method--The essential idea of the method is to cause a confined mass of air, motionless within itself, to be accelerated at a known rate, and to observe photographically the effect of this acceleration on the movement of lint particles falling through the air. The apparatus designed for this purpose is illustrated in Figures 2 and 3.

Two Crown Graphic cameras with f/4.7 Wollensak lenses and electrically synchronized shutters are mounted firmly as shown, on a solid plywood base three feet square. Similarly mounted on the same base is a fully enclosed box one foot square and two feet high, the purpose of which

is to contain the mass of air to be accelerated. The side of the box next to camera A is transparent; the other three sides are lined in black, except for a narrow vertical transparent slit on the right side, through which light enters from a stroboscopic gas-discharge lamp attached outside. Camera A is focused on the illuminated portion of the interior of the box; lint particles are introduced into this lighted field from tissues attached to the inner portion of a rod running through the upper part of the box. Camera B is focused on a wall scale whose purpose is to indicate the movement of the apparatus. A baffle between the lamp and camera A prevents glare on the lens, but extraneous light is allowed to travel in the opposite direction in order to illuminate the wall scale. This scale is sloped (see Fig. 2) to prevent the overlapping of successive images; distance calibrations, however, are measured along the horizontal to facilitate calculation. The plywood base with attached apparatus rolls freely on a long, smooth table parallel to the wall on which the scale is drawn. Approximately uniform acceleration is provided by the system of weight and pulleys shown in Figure 2. When the moving assemblage is carried to the extreme right, the weight is lifted a distance equal to one-half the length of the track; when released from this position, the apparatus is immediately accelerated toward the left at a rate dependent upon the size of weight used.

In producing photographs suitable for the evaluation of the inertial behavior of lint particles, the following procedure was used: The apparatus was set up in a darkened room. With the mobile assembly held firmly in position for instant application of the accelerating force, lint particles were introduced into the top of the box by agitating the tissue-wrapped rod. After the passage of a few seconds to allow the largest particles to fall from the field to be photographed, the stroboscopic light was set blinking at a uniform rate of 15 flashes per second, and the shutter of camera A was opened. One second later, camera B (set for a one-second exposure) was opened, and the apparatus simultaneously released. The apparatus was stopped at the end of the track by two assistants, and camera A closed by hand, completing the run. The photographs from camera A are two-second exposures, the first second of which shows the trajectories of particles falling in still air, and the remaining second of which shows the same trajectories as deflected by the uniform acceleration of the air. Trajectories are measured with a scale provided by photographing a meter stick in the same field. The photographs from camera B are one-second exposures showing the wall scale in a series of relative positions from which the acceleration of the apparatus can be evaluated. Figure 4 shows typical photographs from cameras A and B.

Sixteen pairs of photographs were produced with this apparatus, with the accelerations ranging from 196 cm/sec^2 to 443 cm/sec^2, or approximately 20 to 45 per cent of the acceleration of gravity. In addition, several photographs were taken with camera A alone, without acceleration.

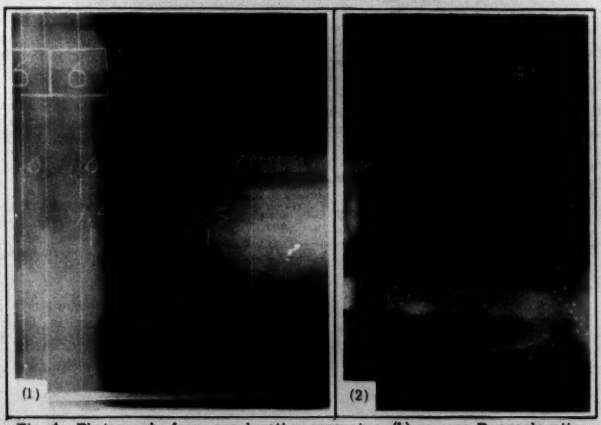


Fig. 4--Photographs from acceleration apparatus; (1) camera B, acceleration is shown by increasing distances between vertical lines, the full length lines being caused by a division in the blackboard on which the scale was drawn; (2) camera A, particle trajectories before and during acceleration

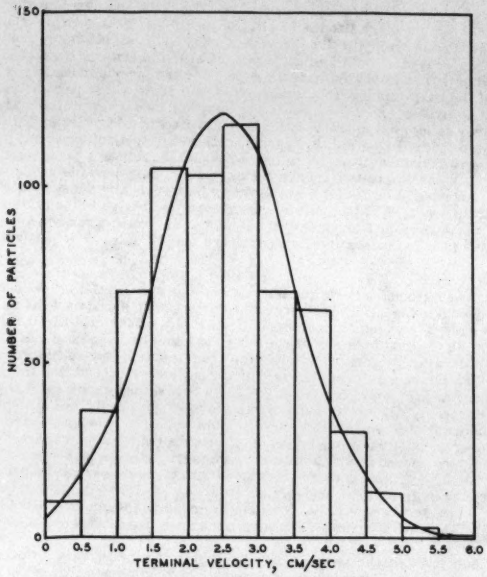


Fig. 5--Distribution of terminal velocities, 624 particle trajectories from 18 photographs; curve approximating distribution

The terminal velocities of fall were computed for the trajectories, both before and during the acceleration period. No consistent change in the vertical component of motion was brought about by the application of the horizontal acceleration; hence the components of motion may be treated independently if desired.

The distribution of terminal velocities from more than 600 trajectories taken at random from all available photographs is shown in Figure 5. The distribution may be approximated by a normal curve, necessarily bounded on the lower side by the zero point. The standard deviation from the mean velocity of 2.5 cm/sec is 1.0 cm/sec. This means that approximately two-thirds of all the particles photographed have a terminal velocity between 1.5 and 3.5 cm/sec.

Measurements were next made to determine quantitatively the effects of the air accelerations on the trajectories of the particles. Actual measured data consisted of the terminal velocity of fall before and during acceleration, and the horizontal component of velocity caused by the acceleration of the particle relative to the air. An analysis of these data was made following the line of reasoning indicated in subsequent paragraphs.

Theory--A particle of mass m falling through air is acted upon by a downward force mg due to gravity and an upward force F due to drag, or the force of resistance resulting from the viscosity of the air. When the particle reaches its terminal velocity, the two forces are balanced, that is,

$$F = mg \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

The drag on an object moving through a fluid is a function of the velocity V of the motion relative to the fluid [D'ALEMBERT, 1752; 1777]. It may be assumed [KOOEY and UYTENBOGAART, 1946] that the drag is proportional to some power n of the velocity, or

$$F = kV^n \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

In the case of the particle moving at its terminal velocity W

$$F = kW^n \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

where W is positive downward. From (1) and (3)

$$k = mg/W^n \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

The product of the mass and the vector acceleration of a particle is equal to the sum of the drag force and the force of gravity, that is

$$m(D\vec{V}_p/Dt) = k\,[(\vec{V}_a - \vec{V}_p)/(|\vec{V}_a - \vec{V}_p|)]\,(|\vec{V}_a - \vec{V}_p|)^n + m\vec{g} \quad \ldots\ldots\ldots\ldots \quad (5)$$

Table 1--Values of the exponent n in Eq. 6 for individual particles at various accelerations and terminal velocities

Particle number	Acceleration applied	Terminal velocity, W[a]	Relative horizontal velocity, $u_a - u_p$	n (computed)
	pct of g	cm/sec	cm/sec	
1	20	1.04	0.21	0.98
2	20	4.86	0.97	1.00
3	20	2.94	0.59	1.00
4	20	3.52	0.70	1.01
5	20	2.76	0.55	0.99
6	37	4.48	1.71	0.93
7	37	2.77	1.05	0.95
8	37	1.43	0.53	1.00
9	37	3.98	1.52	0.93
10	37	1.90	0.76	0.87
11	37	1.71	0.67	0.89
12	37	1.14	0.42	1.00
13	37	2.09	0.76	1.02
14	37	2.02	0.76	0.98
15	37	1.81	0.67	0.99
16	40	0.59	0.23	1.04
17	40	4.39	1.88	0.93
18	40	5.50	2.19	1.06
19	40	2.24	0.92	1.01
20	40	5.25	2.10	1.05
21	40	2.19	0.87	1.07
22	40	1.78	0.72	1.03
23	40	2.00	0.81	1.02
24	40	4.48	1.90	0.94
25	40	0.95	0.38	1.05
26	40	2.10	0.83	1.07
27	40	4.88	2.10	0.92
28	40	4.41	1.90	0.92
29	40	4.05	1.62	1.05
30	40	1.50	0.60	1.04
31	40	2.47	0.99	1.05
32	40	3.48	1.39	1.03
33	40	1.95	0.79	1.03
34	40	0.85	0.34	1.06
35	40	2.62	1.05	1.05
36	45	3.44	1.54	1.01
37	45	2.49	1.12	1.00
38	45	2.10	0.95	0.99
39	45	3.20	1.52	1.02
40	45	3.62	1.62	1.01

[a]Where a measurable difference occurred, values of W were taken from the undeflected portion of the trajectories.

where D/Dt is the rate of change following the particle, $\vec{V}_a$ the velocity of the air, and $\vec{V}_p$ that of the particle. The drag acts oppositely to the relative velocity, $\vec{V}_p - \vec{V}_a$, or in the direction of the unit vector $(\vec{V}_a - \vec{V}_p)/(|\vec{V}_a - \vec{V}_n|)$, and is assumed proportional to the nth power of the absolute magnitude of the relative velocity. The proportionality factor, k, may be replaced by (4) and (5) becomes

$$D\vec{V}_p/Dt = (g/W^n)\,(|\vec{V}_a - \vec{V}_p|)^{n-1}\,(\vec{V}_a - \vec{V}_p) + \vec{g} \quad \ldots\ldots\ldots\ldots\ldots (6)$$

All values of velocities and accelerations in this equation can be measured from the experimental photographic data described above; hence n can be computed.

Computations of the value of n in (6) for the accelerations mentioned above have been made from 40 particle trajectories, and it is found that n generally is equal to one, within the limits of experimental accuracy. Actual computed values for the individual particles are shown in Table 1. Occasional fairly large departures from the unit value may in individual cases be attributed to the particle having significantly differing drag faces in different directions. The data show that this occurs infrequently.

Substituting n = 1 in (6) gives

$$D\vec{V}_p/Dt = (\vec{V}_a - \vec{V}_p)g/W + \vec{g} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

or in component form

$$Du_p/Dt = (u_a - u_p)g/W \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (7a)$$

$$Dv_p/Dt = (v_a - v_p)g/W \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (7b)$$

$$Dw_p/Dt = (w_a - w_p)g/W - g \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (7c)$$

where w is the upward vertical velocity. These equations may be used in evaluating the errors inherent in the photographic technique.

Evaluation--The errors introduced in computations of turbulence factors from lint-particle data may be divided into three categories:

(1) The error in the vertical component of velocity due directly to the terminal velocity of fall.

(2) The error in the horizontal components due to the fact that a given particle is by reason of its finite terminal velocity associated with a different air parcel for each difference in time.

(3) Errors in all three components due to the lag of the particle motion behind the air motion.

The first error is the largest and most easily accounted for. Since the mean terminal velocity of all particles is -2.5 cm/sec, mean vertical velocity components may be corrected to a high degree of accuracy by simply subtracting this figure. Individual point-values may be approximated by the same method. The second and third sources of error are more difficult to evaluate exactly; their relative importance, however, may be estimated by integrating (7a) for special cases.

To estimate the second error, let us consider a particle falling at terminal velocity W through a field whose velocity in the horizontal x-direction is zero at level zero, and increases linearly downward. The velocity, u_a, of the air at any point in this field can be represented by

$$u_a = -az$$

where a is a positive constant, and the z-axis is positive upward. The rate of change of the air velocity following the motion of the falling particle is then

$$Du_a/Dt = Wa$$

Hence

$$U_a = Wat$$

From (7a), the differential equation of the particle motion in the horizontal now becomes

$$Du_p/Dt = (Wat - u_p)g/W \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

For $u_p = 0$ at $t = 0$, the solution of this equation can be written

$$u_p = Wat - W^2a/g + (W^2a/g)e^{-gt/W} \quad \ldots\ldots\ldots\ldots\ldots\ldots (9)$$

where e is the base of natural logarithms; and the ratio between the velocity of the particle relative to the air and the velocity of the air is

$$(u_a - u_p)/u_a = (W/gt)\,(1 - e^{-gt/W}) \quad \ldots\ldots\ldots\ldots\ldots\ldots (10)$$

For a terminal velocity of 2.5 cm/sec, the value of this ratio at the end of one second becomes - 0.25 per cent, and it is correspondingly smaller for larger values of time. Thus the error due to this cause is smaller than the probable error in measuring [MILLER, BADGLEY, and SINGER, 1949].

A similar procedure can be followed in estimating the third source of error, that brought about by particle lag. Let us consider a particle associated with an air parcel which, starting from rest, undergoes a constant horizontal acceleration, expressible as some fraction of the acceleration of gravity, thus

$$du_a/dt = bg$$

where d/dt is the rate of change following the air motion, and

$$u_a = bgt$$

since u_a is initially zero. By an integration similar to that above it can be shown that the velocity of the particle is given by

$$u_p = bgt - bW\,(1 - e^{-gt/W}) \quad \ldots\ldots\ldots\ldots\ldots\ldots (11)$$

and the ratio of the velocity of the particle relative to the air and the velocity of the air is

$$(u_a - u_p)/u_a = (W/gt)\,(1 - e^{-gt/W}) \quad \ldots\ldots\ldots\ldots\ldots\ldots (12)$$

If the acceleration being considered acts in the vertical direction, the differential equation is (7c), which, for $w_p = -W$ at $t = 0$, yields the solution

$$w_p = cgt - cW - W + cWe^{-gt/W} \quad \ldots\ldots\ldots\ldots\ldots\ldots (13)$$

where c is a constant analogous to b in (11), and $w_a = cgt$. In this case that portion of the particle lag due to the acceleration of the air is $w_p + W$, and the ratio corresponding to (12) is

$$[w_a - (w_p + W)]/w_a = (W/gt)\,(1 - e^{-gt/W}) \quad \ldots\ldots\ldots\ldots\ldots\ldots (14)$$

In either case the ratio (12) or (14) has the same value as (10), and the percentage error due to particle lag under constant acceleration in any direction is the same as that due to the particle falling through a linearly increasing velocity field. The total error due to both causes can be no greater than their arithmetic sum; that is, one half per cent, for the values of t and W previously assumed.

Conclusions--Three inaccuracies occur in the raw data of turbulence analyses from photographs of floating particles. These inaccuracies have been evaluated for Kleenex particle trajectories by a study of experimental data. They are:

(1) The existence of a finite rate of particle fall causes a direct error in the vertical component of eddy velocity computations; this error can be evaluated and accounted for in the mean to a high degree of accuracy.

(2) The same cause leads to an error in computed values of horizontal velocity components, since the particle, in falling through the air, is identified with a different air parcel at each point in its trajectory.

(3) All measurements are subject to a slight distortion due to the inertial lag that occurs when a particle is subjected to an acceleration.

The second and third factors have been shown to be negligibly small in comparison to the probable error in measuring [MILLER, BADGLEY, and SINGER, 1949].

In its present state of development the photographic method is the most sensitive and probably the most accurate method of measuring the details of turbulence yet devised. The need for improvement lies largely in the type of particle used. If small, spherical particles of very low density, but having good photographic qualities, could be discovered or developed, the errors in the system could be reduced to very low proportion. Until this improvement can be made, it is well worth while to continue the study on its present level.

Acknowledgments--The experimental work described in this report was carried out with the aid of the facilities of the Atmospheric Energy Project, sponsored jointly by the College of Engineering, New York University, and the United States Weather Bureau. The material presented is based upon a thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Meteorology, College of Engineering, New York University.

References

BADGLEY, F. I., The kinetic energy of small scale air motions, New York University, 1950 (unpublished).

D'ALEMBERT, J., Nouvelle theorie de la resistance des fluides, David, Paris, 1752.

D'ALEMBERT, J., Nouvelles experiences sur la resistance des fluides, Chardon, Paris, 1777.

HALL, W. A., and H. F. POPPENDIEK, Review of some of the recent fluid turbulence contributions reported in the literature, Department of Engineering, University of California, Los Angeles, 1949.

KOOEY, J. M. J., and J. W. H. UYTENBOGAART, Ballistics of the future, Technical Publishing Co., H. Stam., Haarlem-Holland, 1946.

MILLER, J. E., F. I. BADGLEY, and I. A. SINGER, A photographic technique for analyzing turbulent motions of air, New York University, 1949 (unpublished).

MILLER, J. E., Experimental studies in small scale turbulence, Res. Div., College of Eng., New York University, 1950.

REYNOLDS, O., On the dynamical theory of incompressible fluids, and the determination of the criterion, Phil. Trans. R. Soc. London, v. 186, p. 123, 1895.

P. O. Box 5277,
State College Station,
Raleigh, North Carolina

(Communicated manuscript received April 13, 1951;
open for formal discussion until May 1, 1952.)

Transactions, American Geophysical Union Volume 32, Number 6 December 1951

THE VARIATION OF THE GEOMAGNETIC-ACTIVITY RECURRENCE INTERVAL WITH THE SOLAR CYCLE

Edwin J. Chernosky

Abstract--A Chree-method analysis of recurrences of geomagnetic activity was made with a combination of variables heretofore unreported, using data for the years 1932-46. The results indicate that the prevailing interval between geomagnetic disturbances decreases from 28 1/2 days at the start of a sunspot cycle to 26 3/4 at the end, a greater variation than the three per cent previously reported. The recurrence tendency for geomagnetic activity was found to be a minimum at sunspot maximum. Unlike other analyses, this one makes use of a large range of C values in the disturbed- and in the quiet-day categories, and it breaks the sunspot cycle into groups consisting of two and three years.

Introduction--One aspect of the study of geomagnetic activity is concerned with its recurrence interval, corresponding to the elapsed time between successive appearances opposite the Earth of any one active solar area. The interval between successive central meridian passages (CMP) of any one sunspot has, however, a variation in length during the solar cycle greater than the variation in the magnetic-activity recurrence interval as reported by several investigators. While the average interval between CMP for individual sunspots is 27.3 days, a sunspot at high solar latitudes may have an interval of as much as 30 days between CMP. At low latitudes the CMP of any one spot can recur at an interval of as little as 24 days [CHAPMAN and BARTELS, 1940, p. 170]. The mean sunspot synodic-rotation period (the interval between CMP averaged for a number of spots) is reported to be 26.4 days for spots at 0° latitude, and 28.7 days at 35° latitude [CHAPMAN and BARTELS, 1940, p. 169]. It is expected that the prevailing recurrence interval would decrease in length as the mean latitude of the spots decreased in accordance with Spoerer's law. The first spots of a cycle appear at high latitudes. As the cycle advances, new spots appear at progressively lower latitudes. At the end of the cycle, the sunspots of that cycle appear near the equator and spots of a new cycle erupt at high latitudes.

Various investigators have made use of Chree's superposed epoch method and other methods in studies of the recurrence of magnetic disturbance. The writer has made a Chree-type analysis, with a combination of variables not heretofore reported.

Analysis by Chree method of superposed epochs--The Chree method is described in CHAPMAN and BARTELS [1940, p. 396] and CHREE [1913, p. 97]. It consists of a tabulation of days in the manner shown in Table 1. Column n shows the activity of each of several days having no given time interrelationship, but selected on the basis of their activity. Each row of figures shows the day-by-day activity of a chronological sequence of days that includes the n day. Each one of the columns then pertains to days having a particular chronological relationship to the selected days in the n column. The average of each column may usually be considered as representative of a day having that column's chronological relationship to a day of the selected n day's characteristic. The international magnetic character figures (C) are used in Table 1 and in this investigation. They are described by BARTELS [1932, p. 2].

Arrangement of the data--Short portions of the solar cycle should encompass proportionally small changes of the mean latitude of solar activity. In order to minimize the effect of any unsystematic variation during the one complete cycle investigated, the portions segregated in this

Table 1--Abbreviated example of the Chree method, n day C ≥ 1.2

Day	n-33	....	n-1	n	n+1	n+2	n+3	n+4	n+5	n+6	n+7	....	n+33
Jan. 3	....	....	0.7	1.8	1.2	0.7	1.2	1.2	0.5	1.0	1.5	....	....
Jan. 4	....	....	1.8	1.2	0.7	1.2	1.2	0.5	1.0	1.5	1.4	....	....
Jan. 6	....	....	0.7	1.2	1.2	0.5	1.0	1.5	1.4	1.2	0.3	....	....
Jan. 7	....	....	1.2	1.2	0.5	1.0	1.5	1.4	1.2	0.3	0.2	....	....
Jan. 10	....	....	1.0	1.5	1.4	1.2	0.3	0.2	0.3	0.8	1.2	....	....
Jan. 11	....	....	1.5	1.4	1.2	0.3	0.2	0.3	0.8	1.2	1.7	....	....
Jan. ...	....	....	....	....	....	....	....	....	....	....	....	....	....
Means	....	....	1.15	1.38	1.03	0.82	0.90	0.85	0.87	1.00	1.05	....	....

study (called subgroups) were made not shorter than two years. A large range of the high C figures was included in the disturbed-day category to provide a quantitatively representative number of reference days in each subgroup. The frequency distribution of C figures is such that the great majority are small valued. This skewed frequency distribution of the C figures is largely counterbalanced by the definition of C, however. The midscale C value of 1.0 is usually defined as denoting a moderately disturbed instead of an average condition; hence a large range of the less numerous high C figures and a small range of the more numerous low C figures are classified here as those denoting disturbed and quiet conditions respectively.

In selecting the reference days, a day with C 1.2 or greater was considered disturbed, and one with C 0.3 or less, a quiet day. C figures of 0.4 through 1.1 constituted the intermediate-disturbance level reference days. The daily C figures for the years 1932-46, compiled in CHAPMAN and BARTELS [1940, Table J] and JOHNSTON, SCOTT, and BALSAM [1948], were punched into IBM cards. After assembling the cards into two- and three-year subgroups, each of these subgroups was sorted according to the reference-day value into quiet, intermediate, and disturbed categories. All the values in the cards of each category of each subgroup were summed and averaged on the IBM machines to the requirements of the Chree method. Days from 39 days before (n-39) to 39 days after (n+39) n day were included for study, but only the sequence of days of interest was graphed.

The years were grouped as follows: 1932-34 and 1942-44 as low-latitude-spot years; and 1935-36 and 1945-46 as high-latitude-spot years. Sunspot minima occurred in 1933.8 and 1944.2 [McNISH and LINCOLN, 1949, p. 674]. The groups of years 1937-39 and 1940-41 represented sunspot maximum and post-maximum years respectively and covered the intervening latitude spots. The year 1934, with both high- and low-latitude activity, was considered a low-latitude year. As active areas in low solar latitudes pass more nearly opposite the Earth than does high-latitude activity, it is assumed that low-latitude active areas are more effective terrestrially because of some directivity of solar emission. The minimum year 1944 appeared to include most of the remainder of the expiring cycle, so that the following year was classed as one of high-latitude activity, although 1934 and 1945 both might have been considered as years having solar activity of indeterminate-latitude characteristics.

Results--The results by categories are graphed in Figures 1 and 2. The interval obtained by averaging the n positions of the peak or trough values of the two groups of years at the ends of the two cycles (1932-34 and 1942-44) is 26.6 days for the disturbed- and 27.2 days for the quiet-reference-day categories, the former being, for example, the mean of 28, 26, 26, and 26-27 days. The intervals obtained by averaging the positions of these values of the two two-year groups at the beginnings of the two cycles, were 28.7 days for the disturbed- and 28.2 days for the quiet-reference-day categories. The length of the individual recurrence interval for any subgroup ranges from 26 to 30 days. A smoothing of the values (short dashed lines in Figures 1 and 2) would show intervals with lengths of 26 1/2 to 29 days.

The disturbed-day category contained from 12 to 23 pct of the days, and the quiet-reference-day category from 27 to 36 pct of the total days, in each subgroup. The intermediate reference days constituted from 29 to 49 pct of the total days. The standard error (standard deviation/$\sqrt{\text{number of cases}}$) ranged from 0.023 to 0.050 unit of C for the different subgroups.

The ratio of the combined antecedent and subsequent peak values to the selected-day values (values of the departures from the subgroup averages), which is taken as a measure of the recurrence tendency, is shown in Table 2. The lowest and the highest ratios are found in the years of maximum and minimum sunspot count respectively.

Table 2--Recurrence tendency of geomagnetic activity

Item	1932-34	1935-36	1937-39	1940-41	1942-44	1945-46
Reference day C $\geq$ 1.2[a]	0.42	0.27	0.12	0.22	0.34	0.15
Reference day C $\leq$ 0.3[a]	0.40	0.22	0.12	0.29	0.39	0.12
Auto-correlation coefficients[b]--	0.36	0.22	0.11	0.20	0.34	.....
--From these n days	26-27	28-29	27-28	27-28	26-27	.....
Average sunspot number	8	58	104	57	19	63

[a]Ratio of combined maximum antecedent- and subsequent-day pulses to selected-day pulses in terms of departures from subgroup values.

[b]Averaged from data by SHAPLEY [1947].

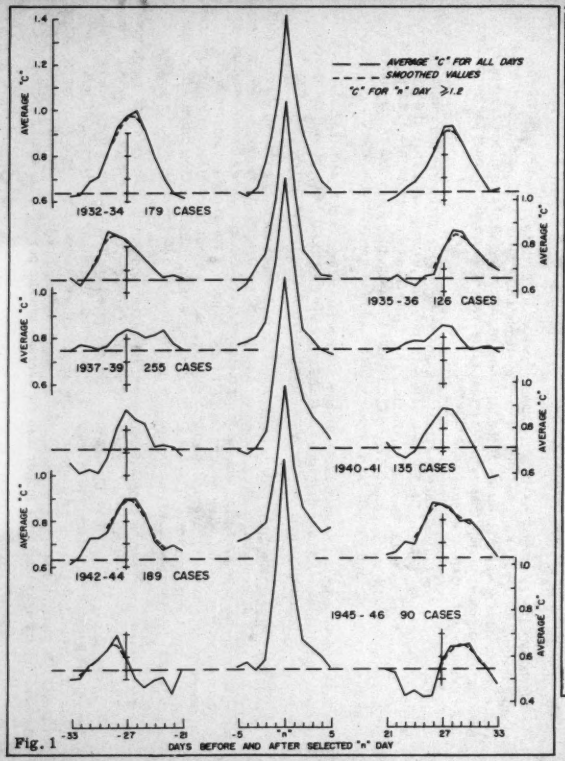

AVERAGE "C" FOR ALL DAYS
SMOOTHED VALUES
"C" FOR "n" DAY ≥1.2
AVERAGE "C"
1932-34 179 CASES
1935-36 126 CASES
1937-39 255 CASES
1940-41 135 CASES
1942-44 189 CASES
1945-46 90 CASES
-33 -27 -21 -5 "n" 5 21 27 33
DAYS BEFORE AND AFTER SELECTED "n" DAY

Fig. 1

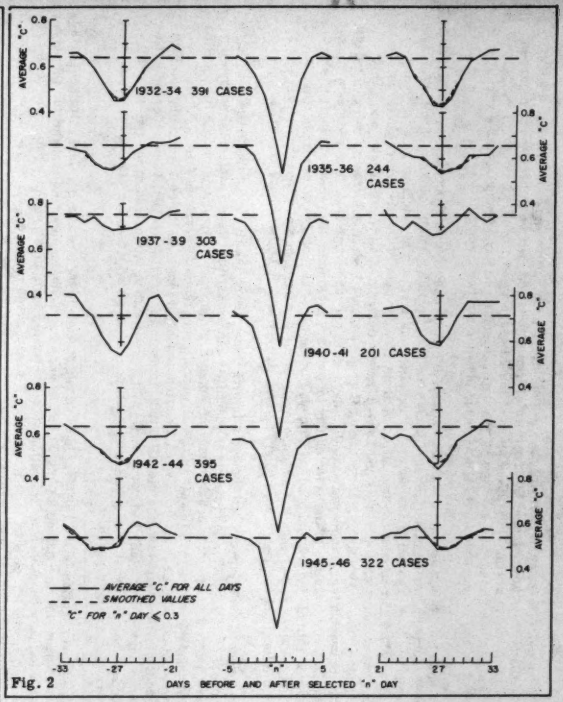

AVERAGE "C"
1932-34 391 CASES
1935-36 244 CASES
1937-39 303 CASES
1940-41 201 CASES
1942-44 395 CASES
1945-46 322 CASES
AVERAGE "C" FOR ALL DAYS
SMOOTHED VALUES
"C" FOR "n" DAY ≤ 0.3
-33 -27 -21 -5 "n" 5 21 27 33
DAYS BEFORE AND AFTER SELECTED "n" DAY

Fig. 2

Figs. 1 and 2--Recurrence intervals as shown by the Chree method

Discussion--In an early study of the latitude effect upon the recurrence interval, CHREE and STAGG [1928] likewise used C. Their reference days were the five international disturbed days of each month during 1906-25. Eleven of the 20 years were classified as a high-latitude group and the remaining nine as years of low-latitude solar activity. No appreciable variation in the length of the recurrence interval was found between the two groups.

In one of the other attempts to find a latitude effect comparable to expectations, ARCHENHOLD [1939] conducted a series of studies by Chree's method, involving the breakdown of the solar cycle into from two to eleven parts and the use of two different methods of selecting reference days. In one study, which indicated a latitude effect of about five per cent of the recurrence interval, two groups of four years each (1930-33 and 1934-37) were designated as years of low- and of high-latitude sunspots, respectively. Days having C greater than 1.0 were selected as reference days, and the correspondingly numbered +n and -n days were averaged together. The secondary maximum of activity, relative to the selected day or primary maximum, was found at about 27 days for the low-latitude group, and at about 28 days for the high-latitude group of years. This study, based on C values rather than the monthly levels of disturbance, showed about the largest variation in the length of the recurrence intervals that Archenhold and others have reported.

In a second study, he divided the cycle into 11 parts, using the five most disturbed days of each month of 1884-1937. Each year was identified and grouped by its chronological separation in years before and after the nearest year of sunspot minimum. By interpolating for the location of the secondary maximum for each of the 11 years, recurrence intervals of from 26.9 to 27.6 days were obtained. Each interval was found to compare in length to the corresponding interval between CMP for sunspots at the mean latitude computed for that four- or five-year group. If the reference days in this study had been the C values greater than 1.0 instead of the five most disturbed days per month, it is probable that a latitude effect of over five per cent of the mean recurrence interval would been shown.

In an investigation of the 1926-41 Godhavn and Sodankyla daily mean H values, OLSEN [1948] found a continuous wave having a period of 26 7/8 days at Godhavn only. He thought that this continuous wave may have been an indication of a persistent longitudinal inequality in some solar emission that was effective at high Earth latitudes only, since it was not evident at Sodankyla nor in the same arrangement of C figures.

BENKOVA [1942] studied the daily H ranges recorded at Sloutzk for the years 1878-1939, concluding that the recurrence interval did not vary systematically during the solar cycle and that the recurrence tendency was a minimum at the beginning of the cycle. In his tabulations, however, Benkova listed groups of data that gave recurrence intervals of 26.6 and 28.5 days in years of sunspot minimum and sunspot increase respectively.

The tendency for a disturbance to recur, as gaged by the ratios of empiric to random probability of recurrence, computed from Benkova's data, falls off progressively from the decreasing part of the solar cycle to the ensuing maximum. This same trend appears in SHAPLEY's [1947] autocorrelation coefficients computed from C for 1890-1944. Shapley noted that the recurrence tendency was approximately 180° out of phase with the curve of the sunspot number.

Some evidence for a period of about 30 days has been found in C and in data from the Potsdam Observatory. This evidence is discussed in CHAPMAN and BARTELS [1940, p. 416] but is considered weak, possibly because of paucity of solar activity during that period.

The present investigation--This investigation employed reference days based on C rather than on the five most disturbed days of each month. As a result, smaller disturbances, as well as the moderately active days preceding and following the days of great disturbance in some months, are included as reference days. The designation of a fixed number of reference days per month can include some that have only average magnetic activity, while in other months incomplete sequences of comparably disturbed days will be used. The difference in magnitude of the latitude effect found appears to result in large part from this difference in choice of reference days.

Individual intervals of 26 and 30 days are evident at the ends and at the beginnings, respectively, of the sunspot cycle, as they are expected to occur. Two exceptions to expectations were found in the 1932-34 year-group. Both the +28 day of the disturbed and the -28 day of the quiet-reference-day values departed more from the average of all days than did either the adjoining 26th or 27th days. An interval of 28 or more days is evident in the values of each post-minimum year grouping, however. In general, the recurrence interval decreases in length with the decrease in latitude of the sunspots but may tend to be longer than the average synodic period of the contemporaneous sunspots.

The intervals during 1937-39, the years at or near sunspot maximum, are poorly defined because the secondary peaks and valleys of the Chree-type curves are shallow and broad. If the amplitude of the secondary salient relative to that of the primary or reference day is an indication of the strength of the recurrence tendency, then this group of years (1937-39) has a weaker recurrence tendency than the preceding or succeeding group of years of this cycle. This minimum of the recurrence tendency at the sunspot maximum is evident in the ratios of the combined largest antecedent and largest subsequent pulses to the selected day pulse. Table 2 gives these ratios as well as corresponding subgroup averages of the autocorrelation coefficients that SHAPLEY [1947] computed with the C figures.

The increase in the recurrence tendency in the years from sunspot maximum to sunspot minimum has been ascribed to the decreasing latitude of the active areas, which causes the emission to be directed more toward the Earth. In the pre-maximum years, however, the normal decrease in sunspot latitude is accompanied by a decrease in the recurrence tendency. As these and Shapley's data, as well as the analysis of Benkova's results, all of which are obtained by somewhat different methods, are in good agreement on this trend, it appears very strongly that the recurrence tendency is as much a function of sunspot number as it is of sunspot latitude. The concurrent existence of sunspots and associated active areas in high, middle, and low latitudes in the years at sunspot maximum, with a consequent wide variation in the intervals between successive CMP of individual spots, undoubtedly contributes to a decreased recurrence tendency in the years at sunspot maximum. It should be noted that there are more disturbed days that are followed by disturbed days at sunspot maximum than at other times of the solar cycle, but that this recurrence sequence is least at that time, percentagewise--a point that will be discussed in a later paper.

Conclusions--The results of this investigation indicated a latitude effect on the magnetic-activity recurrence interval somewhat greater than has been reported previously with the use of the Chree method. The periods indicated by smoothed Chree-type curves ranged from 26 3/4 days for the three years at the end to 28 1/2 days for the two years at the beginning of the solar cycle. The 28 1/2-day period may be somewhat longer than the mean synodic period of the contemporaneous sunspots and be due to active areas associated with the sunspots, but located so as to have somewhat longer intervals between CMP than the sunspots. There is the possibility that this longer-than-expected period is due to some peculiarity of the Chree method, or to the use of a fixed range of C figures in selecting reference days for years of different magnetic activity.

It appears that each of two factors contributes to a demonstration with the Chree method of a variation of five per cent in the 27-day recurrence interval, as a latitude effect. One factor is that as few years be selected from each solar cycle for each solar latitude grouping as is statistically practicable. The other factor is that all the days that can be classified as disturbed, or as quiet, on the basis of C values, be included as reference days in their respective categories.

The recurrence tendency for magnetic activity appears to be a function of sunspot number as well as of sunspot latitude, in that the recurrence tendency (per disturbed day) is weaker at sunspot maximum than it is earlier or later in the cycle. The number of days that are followed by a recurrence of similar activity is of course greatest at sunspot maximum.

Acknowledgments--The writer acknowledges the support given by L. R. Alldredge and expresses appreciation to the members of the Mechanized Analysis group for their cooperation and facilitation of the analysis, to E. O. Schonstedt for his assistance, and to E. H. Vestine for suggesting some of the reference material.

References

ARCHENHOLD, G. H., The influence of variability of the mean latitude of sunspots on the recurrence tendency, Mon. Not., R. Astr. Soc., v. 99, pp. 723-729, 1939.

BARTELS, J., Terrestrial-magnetic activity and its relations to solar phenomena, Terr. Mag., v. 37, pp. 1-52, 1932.

BENKOVA, N. P., Recurrence tendency of magnetic storms, Terr. Mag., v. 47, pp. 147-153, 1942.

CHAPMAN, S., and J. BARTELS, Geomagnetism, Oxford Press, 1940.

CHREE, C., Some phenomena of sunspots and of terrestrial magnetism at Kew Observatory, Phil. Trans. R. Soc., v. 212, pp. 75-116, 1913.

CHREE, C., and J. M. STAGG, Recurrence phenomena in terrestrial magnetism, Phil. Trans. R. Soc., v. 227, pp. 21-62, 1928.

JOHNSTON, H. F., W. E. SCOTT, and E. BALSAM, Geomagnetic indices, 1940-47, Int. Assn. Terr. Mag. Elect., Bull. 12 and 12a, 1948.

McNISH, A. G., and J. V. LINCOLN, Prediction of sunspot numbers, Trans. Amer. Geophys. Union, v. 30, pp. 673-685, 1949.

OLSEN, J., Persistent solar rotation-period of 26 7/8 days in and solar diurnal variation in terrestrial magnetism, Terr. Mag., v. 53, pp. 123-134, 1948.

SHAPLEY, A. H., Recurrence tendency and forecasts of magnetic activity, Trans. Amer. Geophys. Union, v. 28, pp. 715-721, 1947.

Naval Ordnance Laboratory,
Silver Spring 19, Maryland

(Manuscript received May 4, 1951; presented at Thirty-Second Annual Meeting, Washington, D. C., May 1, 1951; open for formal discussion until May 1, 1952.)

Transactions, American Geophysical Union Volume 32, Number 6 December 1951

THE RELATIONSHIP BETWEEN SAND SIZE AND BEACH-FACE SLOPE

Willard N. Bascom

Abstract--A series of diagrams is presented which illustrates the variability of sand size and beach-face slope and the relationship between the two as observed on Pacific Coast beaches of the United States. As a means of standardizing sampling procedures, a "reference point" (the part of the beach face subject to wave action at mid-tide level) was adopted, which permitted satisfactory comparisons of beach characteristics. Distribution of sand sizes along and across beaches is described, and slope changes with beach growth and erosion are illustrated. It is shown that beach-face slope is principally controlled by two factors: (1) the size of the sand and (2) the intensity of wave action.

Introduction--Under the sponsorship of the Office of Naval Research and the Beach Erosion Board, a field party of the University of California visited and repeatedly surveyed some 40 beaches on the Pacific Coast of the United States in the years 1944 to 1948 (see Fig. 1). These beaches included steep and flat beaches under winter and summer conditions and in high and low surf. Details of beach conditions from the dunes to beyond the breaker zone were surveyed and noted, sand samples were taken at many points, the effect of surf conditions on each beach was recorded, and an elaborate program of breaker measurements was conducted. A total of about 500 profiles (from dunes to minus 30 ft) was made and over 600 sand samples were taken in the course of these investigations. Details of these activities are described in the reports of the Institute of Engineering Research, University of California, Berkeley. Since these reports had a limited distribution, some of these data, screened to insure reliability, are used here in a somewhat different form. With its irregularities, the Pacific Coast of the United States is thousands of miles long and quite probably includes most of the possible ocean-beach conditions and configurations. The examples used in this paper represent its maximum variations, and it is believed that these graphs will be generally valid for use in comparing beaches throughout the world. The scope of this paper includes only sandy beaches in which sand is defined as ranging in size from 0.05 to 1.0 mm (U. S. Bureau of Soil Classification). Although there are a few pebble, gravel, and cobble beaches on the coast studied, the largest material found on extensive beaches subject to systematic sampling was 0.8-mm sand. It seems reasonable to believe that the curves can be extended smoothly upward when data on beaches composed of coarse material are available. The studies under which these data were obtained are still under way; this is not to be regarded as a final report but rather as a statement of progress to date.

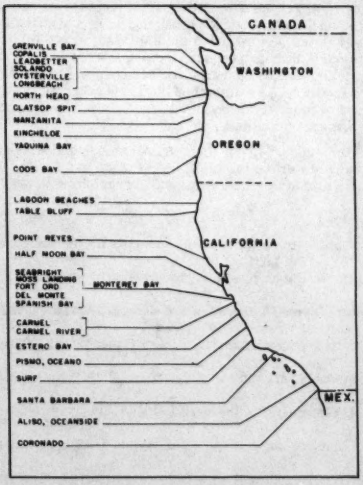


Fig. 1--Location of Pacific Coast beaches investigated for beach slope and sand characteristics

The importance of using standardized measurements can scarcely be overstated and other researchers are urged to consider the use of the "reference point" in future beach examinations so that data will be comparable. This paper is concerned with comparing western beaches of the United States on the basis of median sand size and beach-face slope and shows the probable limits of each. The beach face in this instance is synonomous with shore face or foreshore. The importance of surf action in changing slopes from a profile of deposition to one of erosion is shown, as are the variations in slope with exposure. Finally, Figure 2 gives the observed relation between slope and size.

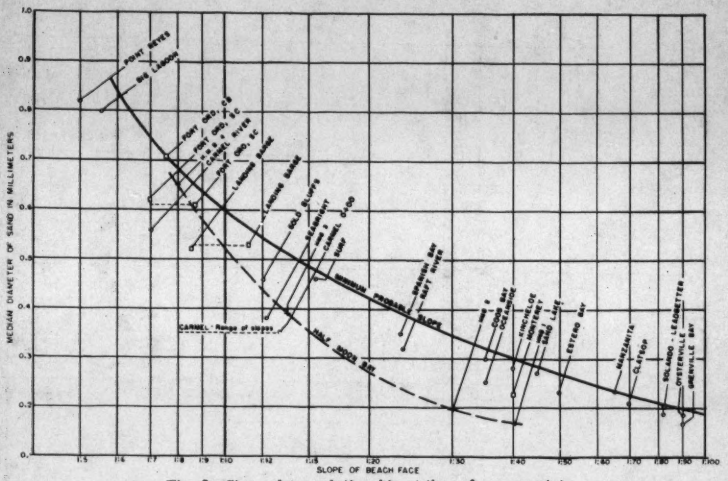


Fig. 2--Size - slope relationship at the reference point

Reference point--The necessity for standardizing beach-sampling and measurement procedures became increasingly evident as data were reduced from widely separated beaches between which it was desirable to make comparisons. The apparently simple job of determining the slope of a beach from a plotted profile raised perplexing questions of how and where to make the measurement. Sand samples from a single beach differed so much in median diameter (because of different sample locations) that first attempts at correlation were failures. Eventually, however, after the mass of data was plotted in various ways, patterns began to take shape. This work ultimately led to a decision to standardize on a specific location so that valid comparisons could be made across time and distance. The point selected was the part of the beach face subject to wave action at mid-tide elevation, now known as the "reference point." All slope measurements and sand samples referred to in this paper were taken at that point. The several illustrations discussed below develop the reasons for its selection and indicate the results that may be obtained by its use. Certain advantages are claimed for this technique: (1) A lone investigator with simple equipment can take measurements rapidly and easily. (2) The variables being sampled are those of the present time (the existing waves placed the sand sampled at the slope measured). (3) The inter-tidal beach-face slope seems to be a major criterion for the potential use of the beach. (4) Some previous investigators have used this location and their data are usable for comparison.

The reference zone may be fairly wide; it is deliberately described somewhat loosely as being the part of the beach subject to wave action at mid-tide stage since the technique would be highly impracticable if it were necessary to locate some exact elevation. Any reference point in this zone is presumed to have approximately the same characteristics. Since the backrush is only slightly below the average sea level, and the uprush may be considerably above, these measurements will be somewhat above the mid-tide level. This part of the beach seems to be the most stable, and consistent results can usually be obtained there. Mid-tide refers to a level half way between the previous high tide and the succeeding low. It is convenient to keep this dimension flexible because the intertidal zone on open ocean beaches may be above or below its predicted position; this is caused by piling up of water on a beach by wave action, wind drag on the sea surface, or changes in sea level from barometric pressure gradients. On steep beaches, the reference zone may be as narrow as 20 ft, while on flat beaches it may be over 100 ft wide.

Reference-point measurements and samples are most conveniently made at a low-tide stage. Slopes are measured perpendicular to the water line using simple instruments (a clinometer or Brunton compass and a driftwood board to average out minor irregularities). Sand samples

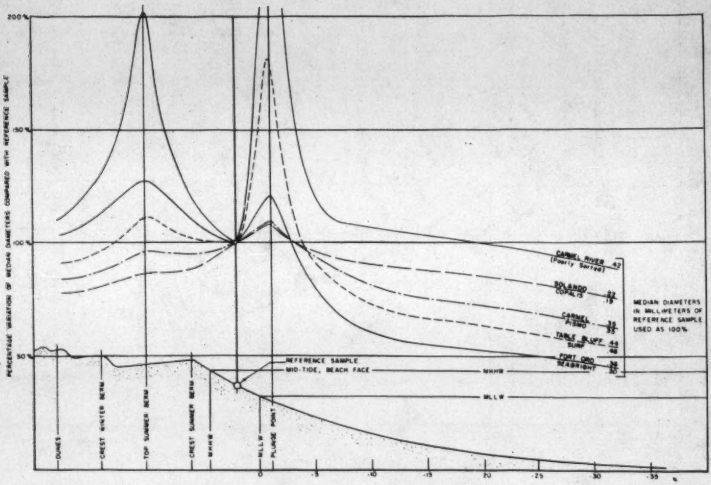


Fig. 3--Size distribution across a beach

should be taken at the same time. It is good practice to scrape away the upper one cm of sand, which often contains coarser material brought by recent swashes, and then take the sample from the top ten cm. A 1000-cc sample is ample, and no special sampling or quartering methods are necessary; quart cardboard cartons are satisfactory as sample containers. Slope, location, and other data can be written on the carton, thus insuring a correct combination of data. All samples mentioned here were subjected to the usual sieve analysis at the Engineering Materials Laboratory of the University of California.

Size distribution across a beach--The concept of a standardized reference point which will permit comparison of sands from widely separated beaches has been described. Figure 3 underlines the necessity for the selection of a specific point and the usefulness of the particular point chosen. From a glance at this figure, it is obvious that it makes a great deal of difference where a sand sample is taken. On a number of beaches sand samples were taken intermittently along the profile from the dunes to 30 ft of water (10 to 20 samples per profile); when plotted, these showed clearly the trends described here. This graphical presentation is a practical means of describing the general case; the stylized profile represents all beaches. A sand sample from the reference point is the zero or reference condition; other samples are plotted by their percentage relationship of their median diameters to the median diameter of the reference sample. At the time of sampling, detailed surveys were made and the sample points were accurately located on the profiles. In Figure 3 the curves have been rounded somewhat so that they represent average conditions and show the unmistakable trends which are characteristic of lateral sorting on ocean beaches. The large variations in the percentages between beaches are not regarded as significant by the author; these are probably due to sorting on the beach and to the size of the largest grains which exist there. The least variations from the reference median are at the beaches which have the smallest sand, and the greatest variations are found at the coarse sand beaches. The largest sand particles at any beach are found at the plunge point just seaward of the backrush, which, observation indicates, is the point of maximum turbulence. The next largest particles are found on top of the summer berm; churned up at the plunge point, the coarse material is held in suspension and carried by maximum uprushes up the beach face and across the crest of the berm from whence it cannot return. The finest sand on the beach is found in the dunes. Under water the sand becomes smaller with increasing depth.

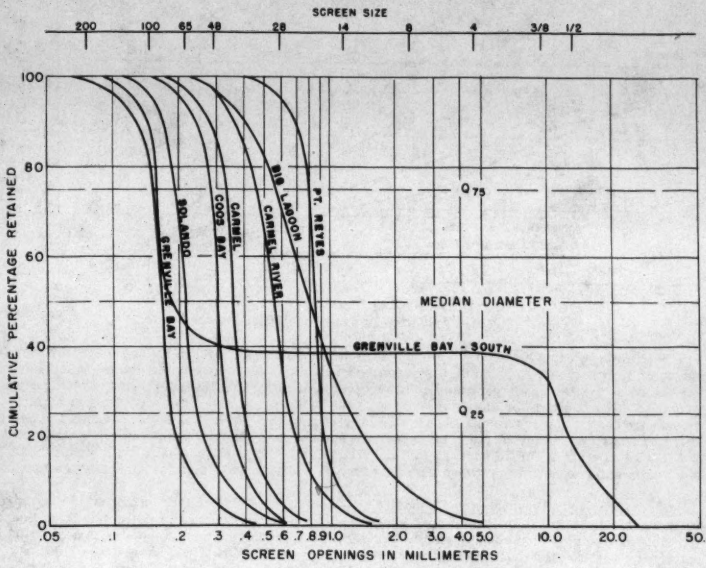


Fig. 4--Size variation of beach sands

Size variations in beach sands--Sands from reference points of Pacific Coast beaches have median diameters which range upward from 0.17 mm. Wave action, even in the most protected locations, seems to remove sand smaller than 0.17 mm from the beach face; the upper limit of 1.0 mm used in this discussion is fixed by definition. The largest sand size sampled was 0.8 mm. Figure 4 illustrates sorting curves which are typical of hundreds made during the investigation. The remarkable degree of sorting performed by wave action is evidenced by the steep slope of the curves and the good sorting coefficients (usually between 1.10 and 1.30). The sorting coefficient is defined as $\sqrt{Q_{25}/Q_{75}}$, where Q_{25} and Q_{75} are the grain sizes at the 25 and 75 pct finer points, respectively, on the size-analysis curve (1.0 = perfect sorting). The fact that sorting is generally very good makes the median diameter an acceptable standard.

Small amounts of both larger and smaller sand exist in each sample. It is believed that these grains are transient and were trapped by the sampling out of their equilibrium environment. Small grains, for example, may have been newly created from the destruction of larger ones and would migrate offshore when exposed to continued wave action. Wave variability also may account for some of the size variation. As might be expected, sorting is somewhat better among the fine sands than the coarse ones; this is probably because of the limits placed by the largest single grains in each case. Since fracturing of large grains can produce sand of any smaller size, the grains which are larger to begin with are likely to be associated with the greatest range of sizes.

The sand-size curve for Grenville Bay is of particular interest since it demonstrates the unusual phenomena of good sorting on two levels. Point Grenville, Washington, is a transition point on the coast; to its north, the beaches are composed of pebbles supplied by the Quinault River; to the south, the beaches are composed of typical Columbia River sand. At the mouth of the Columbia the median diameter is about 0.21 mm. Sand diameters become increasingly small to the north as the source becomes more distant until the finest possible material (0.17 mm) is found in Grenville Bay. Occasional storms, however, move some of the well-sorted pebbles from the beaches to the north around the point and into the bay; in these relatively quiet waters, both are able to exist together.

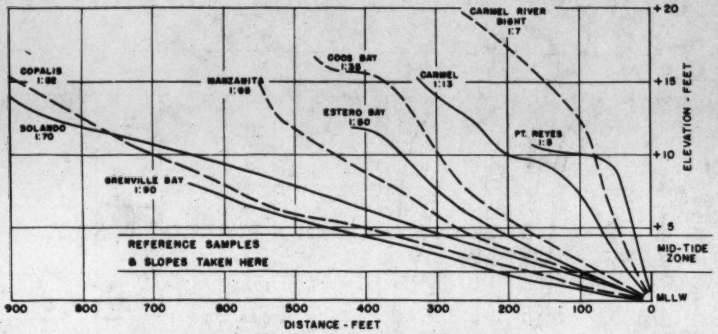


Fig. 5--Variation in sandy beach-face slope

Variation in sandy beach-face slopes--The beach profiles shown in Figure 5 are believed to show the limits of slopes possible for ocean beaches. It is emphasized that these slopes were measured at the reference point and do not include slopes formed by undercutting which can result in a vertical scarp, or slopes on the top of the berm which may have a reverse gradient. Beaches steeper than 1/4 require coarser material than that defined as sand; beaches flatter than 1/100 will not likely be found on exposed ocean shores. Each of the profiles shown is the average of several accurate surveys for the particular beach; surveys were made with transit and stadia and true elevations were carried from U. S. Coast and Geodetic Survey bench marks.

Slope changes with erosion and deposition--The principal difficulty in correlating sand size with beach-face slope is that the slope changes as the beach advances and retreats. Even though the median diameter of the sand remains the same, the beach becomes steeper with deposition and flatter with erosion. Model studies summarized by JOHNSON [1949] show that a relation exists between H_O/L_O values of waves and the characteristic profile of a beach. The conclusion reached was that H_O/L_O values of greater than 0.03 resulted in a "storm" profile (erosion) and that values of less than 0.03 caused an "ordinary" profile (deposition). It seems probable that such a relationship is the controlling factor and that the slope of the beach face responds readily to small changes in H/L values. If an equilibrium state ever exists, it is probably during periods when the waves have H/L values of about 0.03. This gives some clue as to how equilibrium standards may eventually be established; unfortunately H/L data do not exist for each of the points used on these graphs.

Figure 6 shows short-term changes on two beaches which were under close observation during periods of erosion and subsequent deposition. At Carmel, storm seas cut the beach back, flattening it in the reference zone and causing it to steepen near the crest of the berm. This erosion lasted for about one day; by the following day, wave conditions had changed to one favorable to deposition and the beach had steepened and widened. A week after the storm, the beach was wider than before and considerably steeper. Twenty profiles made of this station at weekly intervals throughout the summer of 1946 showed that there was no greater variation in beach-face slope than those caused by this storm.

The Santa Barbara example in Figure 6 shows the cumulative effects of two storms on a beach. The upper, original profile is typical of the summer (depositional) condition; two severe storms in quick succession cut the beach to much gentler slopes.

These bits of information indicate that a relation exists between the slope of the beach (for any given sand size) and the waves impinging upon it. Moreover, it appears that limits can be put on the amount of change (the range of slope) that can be expected for any beach.

The appearance of a beach after a storm emphasizes the need for a definite point at which to make measurements. For example, if a berm was formed during spring tides, and waves causing erosion occurred during the neap tides, a steep scarp may result. The beach will thus appear to be steeper, although it has actually become gentler in the reference zone.

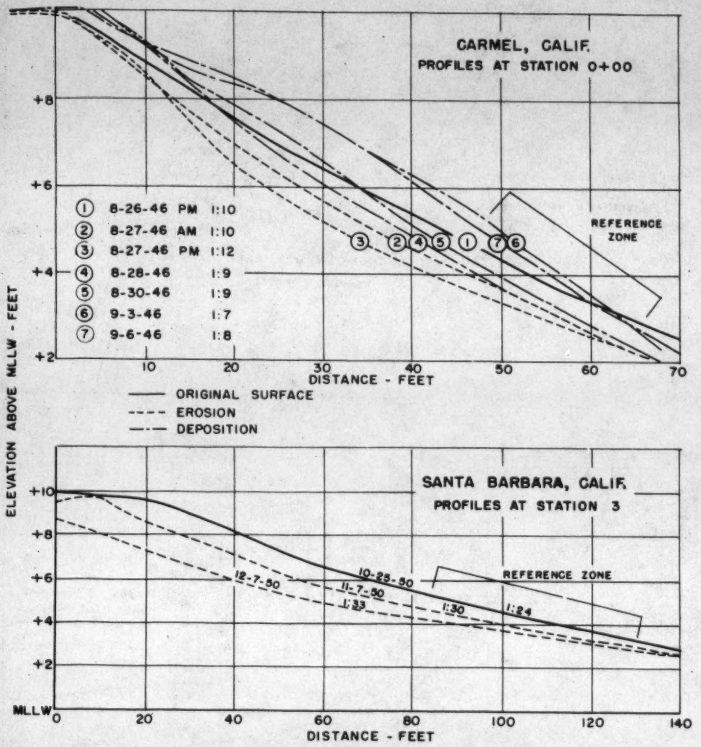


Fig. 6--Slope changes with erosion and deposition

Size and slope variation with protection--The amount of wave energy reaching the point of sampling and measurement is an important factor in determining the equilibrium sand size and the resultant slope of the beach. Waves take the available supply of clastic material and sort and redistribute the components so that the finer materials are ultimately deposited at points of lesser turbulence. In Figure 3 it was shown that the size distribution along a profile followed this rule; the coarsest material was located at the plunge point and the grain size became smaller with a lessening of turbulence in depth. Figure 7 is an example of alongshore sorting. The prevailing swell is from the northwest and considerable protection is afforded to the harbor area (between Profiles 1 and 2) by Pillar Point. South along the beach the protection gradually disappears until at Profile 4 the beach is exposed to nearly the full effect of the prevailing seas. The beach, which is continuous and unbroken, has reacted to fit itself to this environment. At Profile 1, where wave action is at a minimum, the beach is fine-grained (0.17 mm) and flat (1/41 slope). As the beach becomes more exposed, the slopes and sizes respond characteristically. Profile 4 has coarse sand (0.65 mm) and a steep beach face (1/8 slope). This alongshore sorting phenomenon is typical of a dozen or so similar locations, such as San Simeon, Shelter Cove, and Bodega Bay, California; and Cape Lookout, Oregon.

In the discussion of Figure 6, reference was made to changes along a profile caused by varia-

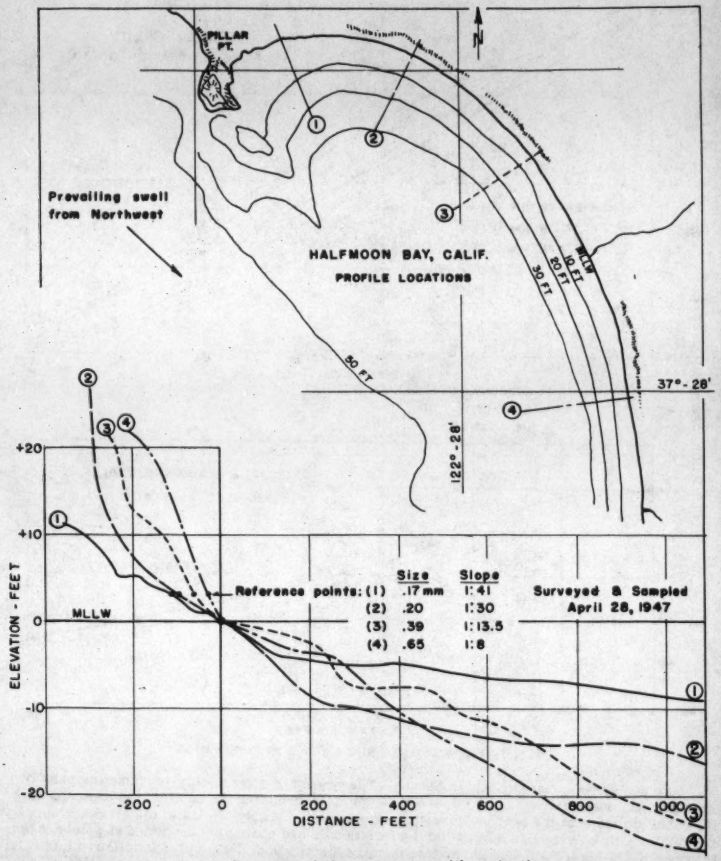


Fig. 7--Size and slope variation with protection

tions in wave action; storm seas cause the beach to flatten, quiet ones cause it to steepen. At first glance, Figure 7 may appear to show the opposite to be true by demonstrating the presence of steep beaches at points of maximum wave action. Sorting and distributing the sand on an extended beach apparently requires considerable time; it is probable that no static state is ever reached and that the sand shifts back and forth along the beach with changes in wave direction. On all of these beaches there is a preponderance of northwest swell (particularly the larger sand-moving waves). Therefore, we can regard each of the Half Moon Bay profiles as being an average of conditions along a half mile or so of beach throughout the year. In short, the long-term situation illustrated is one of approximate equilibrium.

When a storm arises, however, the energy of the surf zone increases and the sand on the

beach face is too small to remain there in this turbulent water. Consequently, it is moved about until it reaches water quiet enough to settle to the bottom; this may be in deeper water or at any place of greater protection. This usually results in the formation of a bar (a storm feature); as the bar grows at the expense of the beach, it influences the waves and eventually causes them to break. As breaker energy is expended on the bar, the water on the beach face becomes less turbulent; this appears to permit the beach to reach another point of equilibrium which is in balance with the storm waves. It is of interest to note that when the sand supply is very large, the result is frequently the formation of three or more bars; where small, the beach is denuded and the back-beach is attacked.

The equilibrium beach face resulting from the storm, as well as that extant during erosion of the beach face, has a gentler slope than normal. It should be pointed out again that the median sand size remained the same throughout the cycle described.

Slope-size relationships at the beach face--A qualitative relationship between the slope of a beach and the size of its materials has long been observed, but a simple correlation between them has been precluded because of the many complexities involved. This paper suggests a standard sampling procedure and shows why it is necessary; it indicates the range of conditions that may be expected; and it describes the variations due to protection and to wave characteristics. There are other factors which undoubtedly have some effect, but in most cases they appear to be negligible; they include shape and density of grains, the stage of tide, and the total supply of sand available. Figure 2 is the first step in assembling this information in a compatible form. Previous work has pointed out this problem; it is the purpose of this graph and discussion to hold out hope for a solution. The limitations are readily admitted, but they emphasize the necessity for specific measurement techniques in the future which will supply the missing data.

The upper curve represents the minimum slope which an unprotected Pacific Coast beach is likely to reach in a storm. Exposed beaches such as Surf, Table Bluff, and Oysterville have slopes approaching this limit much of the time. Beaches such as Carmel, Oceanside, or Seabright, which are protected by their location in embayments or in the lee of offshore islands, can probably never reach it in any ordinary storm condition. The erosional power of waves reaching any point on a beach is a function of the refraction condition and the deep water H/L value. Since the slope is related to the value of H/L (Fig. 6) and to the refraction condition (Fig. 7), the curve of minimum slope represents a level of wave energy. Similar curves would result if each point were assigned a refraction coefficient for the "average Pacific storm" and lines of equal K values were drawn (over a large part of the year the direction is NW and T = 12 sec). The minimum slope curve would about equal the K = 1.0 curve. The distance of any point from the curve is thus seen to be an approximate measure of the intensity of the waves which were shaping the beach face at the time of sampling.

An admittedly more useful curve would be one for the equilibrium condition; at this writing there are insufficient data to make even an approximation; however, the investigations are still underway. Such a curve would determine the trend of a beach, since a point falling on the steep side would indicate building, and a point on the gentle (right-hand) side would indicate erosion.

The curve connecting the Half Moon Bay samples, details of which are shown in Figure 7, is particularly interesting. It is seen to substantiate this discussion by diverging from the curve of minimum slope as protection increases. A moderate northwest storm existed when these profiles and samples were taken, causing the storm profiles shown. If the storm had increased in intensity, the upper points (3 and 4) probably would have shifted to the right. However, if the storm had shifted its direction to the south, the upper points would have remained about the same and points 1 and 2 would have shifted to the right.

Other examples of this variation in slope with protection can be seen; Monterey, Estero Bay, and Manzanita, each with sand median diameters of about 0.23 mm, are distributed by their average protection. Manzanita is well exposed to northern Pacific seas, Monterey is well protected, and the exposure of Estero Bay is about midway between the two.

Conclusions--The following conclusions are justified by studies to this time.

(1) Sandy beach-face slopes (reference zone) on U. S. Pacific Coast beaches range from 1/4 to 1/100.

(2) Median diameter of beach material from the reference point on sandy beaches range upward from 0.17 mm.

(3) As beaches build and erode, the slope of the beach face at the reference point will change considerably, apparently in response to the H/L factor of the waves. An eroding beach will flatten; a building beach will steepen.

(4) Distribution of sand by size along a profile is predictable with reasonable accuracy if the median diameter of sand at the reference point is known. Large grains are found at points of maximum turbulence; sizes get smaller as turbulence decreases.

(5) The slope of the beach face is related to the median diameter of the sand and the amount of wave energy reaching that point. The amount of energy is a function of the refraction conditions; consequently, beaches that are protected are steeper for any given sand size than exposed beaches.

Acknowledgments--The author wishes to give a large measure of credit to his associates, M. P. O'Brien and J. D. Isaacs, who assisted in the planning of this work.

References

BASCOM, W. N., Field studies at Monterey (2 parts), HE-116-224 Inst. of Engr. Research, Univ. of Calif., Oct. 1946.

BASCOM, W. N., Beach and surf conditions on the Oregon and Washington coasts in 1946, HE-116-247 Inst. of Engr. Research, Univ. of Calif., April 1947.

ISAACS, J. D., Beach and surf conditions on the Oregon and Washington coasts in 1945, HE-116-229 Inst. of Engr. Research, Univ. of Calif., April 1946.

JOHNSON, J. W., Scale effects in hydraulic models involving wave motion, Trans. Amer. Geophys. Union, v. 30, pp. 517-525, 1949.

STUMP, R. S., and BASCOM, W. N., Surf observations at Table Bluff, California, HE-116-205 Inst. of Engr. Research, Univ. of Calif., May 16, 1947.

University of California,
Berkeley, California

(Manuscript received May 1, 1951; presented at the Thirty-Second Annual Meeting, Washington, D. C., April 30, 1951; open for formal discussion until May 1, 1952.)

Transactions, American Geophysical Union Volume 32, Number 6 December 1951

WAVE MEASUREMENTS AT THE COLUMBIA RIVER LIGHT VESSEL, 1933-1936

Morrough P. O'Brien

Abstract--Wave observations at the Columbia River Light Vessel during the years 1933 to 1936 are reported. The predominant direction of wave attack is shown to be very nearly perpendicular to the alignment of the shoreline during periods both of accretion and of erosion. In the years intervening since these observations, wave measurements have been made in depths of 40 to 60 ft at a number of localities, but only scattered measurements in deep water have become available. The observations reported here, even though crudely executed, are considered to be reliable as to direction, length, and period; the lengths reported probably should be increased about one-third. Crude as the observations were, they are probably more accurate than are most of the previously reported deep-water observations because the observation point was a relatively small, anchored ship. So far as can be discovered, no other set of observations in deep water at a single location has extended over more than a few days. The record is representative of conditions at sea off the North Pacific Coast.

The entrance to the Columbia River Estuary has been stabilized by the construction of two jetties. After construction of the South Jetty, accretion occurred rapidly on its southerly side, and it was concluded that littoral sand movement was predominantly from south to north. Later, construction of the North Jetty was followed by rapid accretion on its northerly side, suggesting littoral movement from north to south. Subsequently, the south beach was eroded back from its most seaward position. Plans for stabilizing the shoreline and protecting the bases of the jetties required a knowledge of the existence and volume of the littoral drift and of the causes of the changes which had occurred. One approach to these questions was through a study of the relationship between wave energy and direction and the equilibrium plan form of the shoreline. This study was the first effort to relate sand movement to measured wave characteristics and is the only such study to date for which an extended series of wave observations in deep water has been available.

Wave action is the predominant influence in producing littoral drift of sand on ocean shorelines. A sandy shoreline in equilibrium without sand supply should assume a position such that the net sand movement is zero, and this position would appear to be at right angles to the local prevailing direction of wave attack. Three years of wave observation served to establish this predominant direction of wave attack; it was found to be perpendicular to the alignment which the shoreline south of the South Jetty had maintained during its advance and recession.

Since waves are generated by the wind and may travel for great distances before breaking on the shore, the direction, height, length, and period of waves may be expected to show seasonal and annual variations which are as erratic as the wind itself. Consequently, short periods of observation, no matter how accurately conducted, would not provide the desired information. Furthermore, the observations should be made at a distance from shore, where the waves were unaffected by the bottom. The Columbia River Light Vessel is admirably located for this purpose, and the arrangements were made to have data obtained at 08h and 16h daily by the officer on duty. The technique was reduced to the simplest possible terms. Wave heights were estimated against the side of the ship. Very high waves were estimated against the horizon. Several heights were observed and averaged, the number depending on their regularity. Lengths were estimated using the known length of the ship (113 ft) as a scale. Several were estimated, the number depending on regularity. Period was measured by timing ten waves (11 crests) at the bow. The force of the wind was estimated in terms of the Beaufort scale, and the wind and wave directions were reported to the nearest point of the compass. The ship generally headed into the predominant wave train except when strong local winds differed in direction from the underlying swell. Under such conditions the waves due to local winds were reported because the underlying swell was not apparent.

The data were not obtained by trained observers, and the methods used were crude; but the results are believed to be at least relatively, if not absolutely, correct since the entire record was obtained by only a few different observers. About five months were devoted to educating the officers involved, and several visits were made to check their accuracy. Observations covered the period August 1933 to August 1936, but the initial educational period is not included. The ob-

Table 1--Dimensions and periods of waves observed at Columbia River Light Vessel

Month	Percentage of total observations exceeding figure specified								
	20			50			80		
	H_o	L_o	T	H_o	L_o	T	H_o	L_o	T
	ft	ft	sec	ft	ft	sec	ft	ft	sec
January	8.4	310	8.9	5.3	187	7.2	2.9	68	5.6
February	6.6	280	8.4	3.8	130	7.0	1.9	82	4.8
March	8.4	326	9.5	4.4	242	7.5	2.5	159	6.1
April	4.5	227	10.0	2.7	112	7.5	1.3	65	4.8
May	6.2	252	7.9	3.9	172	6.4	2.1	88	5.0
June	5.7	192	7.6	3.3	125	6.0	1.3	71	4.2
July	4.4	275	9.0	2.5	178	6.7	1.2	45	4.0
August	6.1	193	8.1	3.6	168	6.1	1.6	134	4.1
September	6.4	238	8.1	3.8	180	6.5	1.8	78	4.6
October	7.9	293	9.5	4.9	210	6.9	2.4	110	4.6
November	9.9	296	8.5	4.8	223	7.0	2.7	177	4.3
December	10.6	325	9.2	6.3	239	7.2	4.0	153	5.5

H_o = wave height; L_o = wave length; T = wave period between crests.

servations were segregated by months and plotted on a frequency diagram showing the percentage of the total number of observations in each month which equaled or exceeded the magnitude specified. A condensed summary of results appears in Table 1, which is based on exactly two years of record.

The depth of water at the light vessel is 198 ft, and the bottom slope to seaward is three or four degrees. This depth is sufficient to ensure that all waves observed were of the deep-water type, that is, depth greater than half the wave length.

In considering these data, one must recall that any point on the surface of the ocean is usually disturbed by more than one set of waves and that an observer is unable to distinguish between these sets unless they are markedly different in length and height. Since the waves are trochoidal rather than sinusoidal, superposition will result in reinforcement of coincident crests, but where a crest and trough coincide, the crest will still be evident. An observer will report periods and lengths which are less than the correct value for either set of waves. Studies of the effect of superposition [DEFANT, 1929] show very clearly why waves are commonly observed to break in "sets" and why the observed period is less than the true period of any of the component waves.

Local wind waves might completely mask a long, low swell from a distant storm if the observations are made in deep water, but would have no effect on breakers, the period of which would be fixed by the swells because of their greater energy. One would expect, then, that on the average the period observed in deep water would be less than the period of the breakers, and this situation is found to hold at the Columbia River. The wave period in Table 1 that is exceeded 50 pct of the time ranges from 6.1 to 7.5 sec, but breakers of such short periods are observed only infrequently. The average period of the breakers at many points along the Pacific Coast ranges from seven to ten seconds, and observations on the beach near the Columbia River are in agreement with this figure.

The theoretical length of a deep-water wave is related to the period by

$$L_o = 5.12\ T^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (1)$$

Application of this equation to the observations shows that the observed lengths are on the average 75 pct of the theoretical values corresponding to the observed periods. Part of the difference is probably the result of a tendency to underestimate lengths. There is also the effect of superposition of two or more wave trains, which reduces the apparent length and period in the same ratio rather than in the proportions indicated by (1), but this phenomenon would in itself result in observed wave lengths too long in relation to period rather than too short. In view of the good agreement between theory and observation obtained from more precisé measurements, it is believed that the reported wave lengths should be increased by about one-third. The heights reported probably correspond to the characteristic wave or the average height of the highest 30 pct.

The wave heights were an estimated average over an interval, and the effect of superposition

Table 2--Relation of wind speed to average ratio of length to height of wind

Estimated wind speed, Beaufort scale	Ratio of length to height
0 - 2	57.8
3 - 5	43.8
6	19.2

would tend to cancel out. However, an observer would probably give greater weight to the large waves resulting from reinforcement of wave crests. No estimate of this error is possible. The average ratio of length to height decreased with increasing wind speed as shown in Table 2, in which the lengths used are those reported. For reasons stated previously, it is believed that these ratios should be increased about one-third.

The power transmitted by a trochoidal wave per foot of length along the crest is proportional to $H_o^2 \sqrt{L_o}$. This power is available for causing turbulence and suspension of sand in the breakers and for producing and maintaining littoral currents. Examination of Table 1 shows that the average height and length vary through about the same percentage range, and hence from the form of this equation for power we can conclude that the height is of far more importance than the length. The predominant direction can best be approximated by weighting the observations in each direction in proportion to H_o^2. Table 3 shows the percentage of the sum of H_o^2 for waves in each direction to the total in all directions and the percentage of observations in each direction without weighting.

Table 3--Observed wave direction

Direction	Percentage of total observations once 12 months	Percentage weighted in proportion to H_o^2
N	0.73	0.57
NE	1.80	1.44
E	3.18	1.26
SE	2.38	3.30
S	15.02	25.14
SW	18.74	36.36
W	30.03	23.70
NW	16.57	8.24
Calm	11.54	.....

The weighted percentage from south exceeds that from west, but the shape of a plotted curve and the greater duration of westerly waves indicated by the middle column lead to the conclusion that the predominant wave direction as regards the generation of littoral currents and the transportation of sand is west-south-west. This direction is almost perpendicular to the alignment of the beach south of the South Jetty, which is approximately N 28° W.

Thus, the wave observations suggested that the eroding south beach occupied an equilibrium alignment and was not receiving or losing sand by littoral movement. This conclusion led to the hypothesis that erosion was being caused by wind. Measurements of wind drift as a function of wind velocity [O'BRIEN, 1936] combined with long-period wind measurements later fully accounted for the erosion observed.

References

DEFANT, A., Dynamische Ozeanographie, Springer, Berlin, 1929.

O'BRIEN, M. P., and B. D. RINDLAUB, Transportation of sand by wind, Civil Eng., v. 6, p. 325, 1936.

University of California,
Berkeley, California

(Communicated manuscript received April 2, 1951;
open for formal discussion until May 1, 1952.)

Transactions, American Geophysical Union Volume 32, Number 6 December 1951

CORRELATION OF HEIGHTS OF OBSERVED AND COMPUTED DEEP-WATER WIND WAVES IN NORTH ATLANTIC OCEAN AND MEDITERRANEAN SEA

Frank MacDougal

Abstract--An additional proof of the validity of the Sverdrup-Munk technique for forecasting the height of the local deep-water wind waves is presented. The proof makes use of the correlation coefficient and of the similarity of the frequency function curves derived by the use of Craig's method of determining the Pearson-type curve that is involved.

Introduction--In order to justify the conclusions that were reached in a forthcoming study prepared for the U. S. Navy Bureau of Aeronautics, it was first deemed necessary to prove that the computational or forecasting technique for determining the surface winds, and from these winds the resultant local wind waves, was valid for deep-water waves. Swell, or waves that are decaying, are not included in this treatment. Sea heights were to be determined for three locations in the North Atlantic Ocean and one position in the Mediterranean Sea. The forecasting technique was developed by SVERDRUP and MUNK [1947]. Essentially this technique consists of determining the speed and duration time of the surface wind, and then entering a specially prepared graph in which the wind speed is plotted against duration time. The intersection of these two values with a third family of curves then uniquely determines the "significant wave height," defined as the average of the highest one-third waves passing a given point. For waves under 20 ft in height, the height can be effectively determined to the nearest one-half foot. For waves greater than 20 ft the heights can be found to the nearest foot. Detailed examples of this forecasting procedure are given in U. S. HYDROGRAPHIC OFFICE [1951]. The code used for recording the heights of the waves is defined in Table 1.

Table 1--Definition of the code used by the U. S. Navy Hydrographic Office for reporting the height of the sea

Code figure[a]	Height range
	ft
0	0
1	1
2	1 - 3
3	3 - 5
4	5 - 8
5	8 - 12
6	12 - 20
7	20 - 40
8	Over 40

[a]A code figure 9, used after one of the other figures, denotes a confused sea of corresponding height.

The correlation coefficient--For computational purposes the linear correlation coefficient is given by

$$r_{xy} = (N\Sigma xy - \Sigma x \Sigma y)/\sqrt{[N\Sigma x^2 - (\Sigma x)^2][N\Sigma y^2 - (\Sigma y)^2]}$$

where x is the height of the computed waves and y is the height of the observed waves. N is the number of cases under consideration. As an erroneous correlation coefficient of large value can often be obtained from a comparison of two totally unrelated sets of data, a measure of its significance is necessary. This can also be thought of as the range of values to which the coefficient will be confined. The smaller the range, the more significant the coefficient. The measure of this range is called the standard estimate of error and is expressed by

$$SE = (1 - r^2)/N$$

The probable range of values of the coefficient is plus or minus three times the standard error.

Procedure--The observed values of wave heights used in this paper were obtained by a random selection of 650 representative observations from the IBM bank of 2 1/2 million wave observations on file at the Hydrographic Office. By representative is meant that the observations were taken over several sectors of the North Atlantic Ocean and Mediterranean Sea. All wave observations that were obviously in error were discarded; for example, an observation showing a Beaufort 2 wind and a code 8 wave height was not used as this is an impossible combination. Also, if the observed wind was less than ten knots the observations were not used as the computational technique fails at this lower limit. Otherwise, no arbitrary method of selection was employed.

The technique of forecasting the sea height is clearly and completely described with examples

in U. S. HYDROGRAPHIC OFFICE [1951]. The historical series of Northern Hemisphere Weather Maps was used to determine all the parameters necessary for computing the heights of the waves. As the time, date, and location of the observation is known, it is easy to make the computations for the identical time and position. Numerous errors can occur in the computations as, for example, the small scale of the historical maps makes accurate measurements of the isobar spacing extremely difficult, sea-surface temperatures at the point desired are seldom entered in the synoptic reports plotted on the maps, the time of duration of the wind can be in error by as much as 12 hr, and the exact lengths of the fetches and decay distances are difficult to ascertain. Fortunately these errors are not additive.

Two methods of computing the correlation coefficient were used. In the first method the observed code figure was changed to feet. If the computed wave heights came within the range of the code figure, they were considered to be in perfect agreement. Thus if the observed wave had the code figure 4 (5 to 8 ft) and the computed wave height was six feet, the observed wave was considered to be six feet in height. If the computed wave fell outside the range of the observed code figure, then the observed wave was considered to be at the limit of the range. In the above example, if the computed height had been ten feet, the observed height would have been considered as eight feet.

In the second method the observed wave was considered to be always at the midpoint of the range. Thus for code 4 the height is taken as 6.5 ft.

Mathematically, the second method is probably more correct and the correlation coefficient more reliable, as the actual differences between the observed and computed heights are not artificially reduced or obliterated. However, the second method restricts the observed heights to nine values, while the computed heights can take on any number of values.

Discussion--By means of the first method, a correlation coefficient of 0.8864 with a standard error of 0.008 was obtained, giving a range of probable values of the coefficient of 0.8624 to 0.9104. For the second method the coefficient was 0.8104 with a standard error of 0.013, giving a range of probable values from 0.7714 to 0.8494.

Considering the numerous possible sources of error noted above, these results are surprisingly high. As all values were obtained by standard statistical methods, it can safely be assumed that the value of 0.8104 is at the lower limit of the true coefficient while the upper limit may be even higher than 0.9104 since the elimination of any or all of the errors would increase its value.

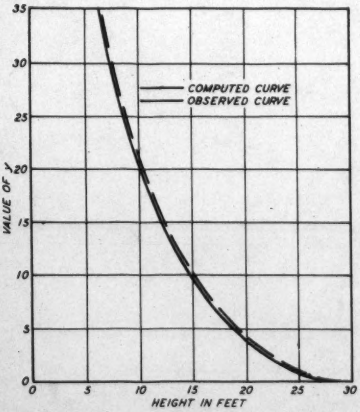


Fig. 1--Graph showing the two particular equations for the computed and observed variates

Curve fitting--By the use of CRAIG's [1936] method it has been determined that the observed and computed variates each form a Pearson-Type I, J-shaped curve. The general curve for this type of function is

$$y = C(t - r_1)^{m_1}(r_2 - t)^{m_2}$$

where

$$C = 1/\beta\,(m_1 + 1, m_2 + 1)\,(r_2 - r_1)^{m_1+m_2+1}$$

The range is from r_1 to r_2, β is the Beta Function, m is the mean, σ is the standard deviation, and t is the standard ordinate given by

$$t = (x - m)/\sigma$$

For the observed waves the particular equation is

$$y = 2.03 \times 10^{-2}\,(t + 0.8611)^{-0.40}\,(4.408 - t)^{1.8534}$$

For the computed waves the particular equation is

$$y = 2.1 \times 10^{-2} (t + 0.8701)^{-0.4093} (4.41 - t)^{1.843}$$

The graphs of these two curves are shown in Figure 1, and it is obvious that they are nearly identical.

Conclusion--With the very close agreement of the two curves of Figure 1 and the high values of the correlation coefficients despite the numerous errors that can enter into the forecasting procedure, the conclusion is that "hindcasting" of wave heights for statistical studies of deep-water wind waves is valid. No conclusion can be reached as to the validity of wave periods found in this manner, since no actual observations were available for comparison.

References

CRAIG, C. C., A new exposition and chart for the Pearson system of frequency curves, An. Math. Stat., v. 7, pp. 16-28, 1936.

SVERDRUP, H. U., and W. H. MUNK, Wind, sea, and swell; theory of relations for forecasting, H. O. Pub. no. 601, Washington, D. C., 1947.

U. S. HYDROGRAPHIC OFFICE, Techniques for forecasting wind waves and swell, H. O. Pub. 604, Washington, D. C., 1951.

Division of Oceanography,
U. S. Navy Hydrographic Office,
Washington 25, D. C.

(Manuscript received April 26, 1951; presented at the Thirty-Second Annual Meeting, Washington, D. C., April 30, 1951; open for formal discussion until May 1, 1952.)

Transactions, American Geophysical Union Volume 32, Number 6 December 1951

CARBON CONTENT AND RADIOACTIVITY OF MARINE ROCKS

Virginia L. Burton and Geraldine R. Sullivan

(Contribution from Research Project 43C of the American Petroleum Institute located at the Massachusetts Institute of Technology; W. L. Whitehead, Director; Clark Goodman, Physical Director)

Abstract--The radioactivity and carbon content of eight geological formations have been determined. Included were two sandstones, two limestones, and four shales. An increasing linear relation was observed between the net beta count and the carbon content.

The origin of petroleum has long been a subject for controversy. In spite of differences in opinions, the general consensus is that most of the oil results from the decomposition of organic material laid down in shallow marine basins. The agents which bring about the degradation of complex organic molecules into simpler hydrocarbon molecules are still largely unknown.

A suggestion was made by LIND and BARDWELL [1926] that the natural radioactivity of sedimentary rocks might be a factor in polymerizing gaseous hydrocarbons, for example, "marsh gas," into petroleum. Later BELL, GOODMAN, and WHITEHEAD [1940] suggested that these radioactive particles might supply the necessary energy to break down the solid and semi-solid organic material in marine sediments into petroleum fractions.

When it appeared from experiments on the effects of alpha particles and deuterons on organic compounds [BREGER, 1948; BREGER and BURTON, 1946; BURTON, 1949, SHEPPARD and BURTON, 1946] that radioactivity could play an important role in petroleum genesis, it became necessary to determine the content of radioactive elements in sediments bearing organic source materials to see if any genetic relationships might exist.

Although considerable work has been carried out on the carbon content and radioactivity of sedimentary rocks [BEERS and GOODMAN, 1944; BELL, GOODMAN, and WHITEHEAD, 1940; TRASK, 1942], little has been done on the correlation of the two sets of data.

Shales, which according to LEITH and MEAD [1915] comprise 82 pct of the sedimentary rocks, have by far the largest concentration of radioactivity. Organic matter, which TRASK [1942] estimates as 1.6 times the percentage of organic carbon, also seems to be concentrated in the shales rather than in limestones and sandstones. Table 1 is a compilation of Trask's data for carbon content, and of radioactivities reported by Bell, Goodman, and Whitehead.

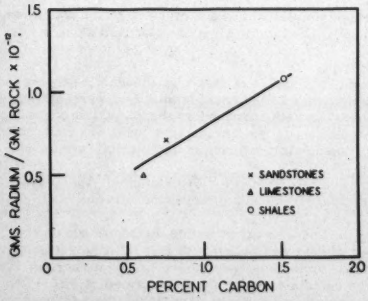


Fig. 1--Relationship between radioactivity and carbon content for sedimentary rocks

Table 1--Radioactivity and carbon content of sedimentary rocks

Rock	Ra gm/gm rock	pct C
Limestones	0.50×10^{-12}	0.61
Sandstones	0.71×10^{-12}	0.76
Shales	1.08×10^{-12}	1.52

When the values from these two sets of data are plotted (see Fig. 1), a linear relationship between carbon content and radioactivity is indicated. The present research, supported first by the Geological Society of America and in later years by the American Petroleum Institute, was undertaken so that both carbon determinations and radioactivity measurements could be made on the same samples. Thus a more significant conclusion might be reached.

Samples

Eight geological formations were selected, four shales, two sandstones, and two limestones.

Miocene nodular shale--The Miocene nodular shale from the Los Angeles Basin in California was obtained in nine core sections varying in depth from 8090 to 8237 ft from a well in the Lawndale field through the courtesy of the Standard Oil Company of California. Geological and chemical evidence [HOOTS, BLOUNT, and JONES, 1935] supports the contention that this oil shale is the most likely source for the crude oil in the basal Miocene conglomerate and schist in the Playa del Rey and other fields.

Cherokee shale--The Cherokee shale of Oklahoma was obtained in eight core sections from wells in and near the Burbank field through the courtesy of the Carter Oil Company and the Phillips Petroleum Company. The Cherokee shale is of Pennsylvanian age.

East Texas Cretaceous--Samples of three formations from the Gulf Series, the Austin chalk, Eagle Ford shale, and Woodbine sandstone, were taken from TRASK's [1942] collection of oil-well cuttings. Depths of samples ranged from 1000 to 4000 ft in 33 wells. The Woodbine sandstone is the oil-producing zone of this region. It is overlain usually by the Eagle Ford shale which, in addition to the shaly horizons in the sandstone, may be a source bed.

Mississippi Cretaceous--Samples of oil-well cuttings were collected from two cores taken at 5- to 25-ft intervals through the Selma chalk, Lower Eutaw shale, and Tuscaloosa sandstone through the courtesy of the Gulf Oil Company. These formations correspond to those sampled for the Cretaceous of East Texas.

Experimental

Total beta emission--Three types of radiations are emitted by natural radioactive elements, alpha, beta, and gamma rays. Beta rays can be measured rapidly, taking only a few minutes instead of the several hours required for alpha-ray measurements. A Tracerlab autoscaler and a bell-type Geiger counter with a thin mica window were used to determine the total beta activity. These measurements were all made relative to a high activity standard in order to normalize for changes in counter efficiency and geometry of the equipment.

Net beta emission (due to U + Th)--The active isotope of potassium, K^{40}, also emits beta rays and therefore it was necessary to determine the potassium content of each sample in order to obtain the net beta activity.

A Perkin Elmer flame photometer was employed for potassium determinations. The sample was put into solution by digesting with HF and H_2SO_4. The solution was then poured into an atomizer and sprayed into the base of an air-acetylene burner. The spectrum of the resulting flame was dispersed by two prisms. Light of the wavelength corresponding to potassium fell on a photocell and the resulting current was amplified for measurement. To increase the accuracy of the measurements a lithium internal standard was used.

The instrument was calibrated by measurements on feldspars and clays of known potassium content obtained from the U. S. Bureau of Standards. Deviations from the standard sample were about 0.02 - 0.10 pct K.

Beta-particle measurements were carried out on a series of prepared standards varying in potassium content, in order to determine the contribution to the count from known percentages of potassium. A straight-line relation was obtained. The beta count due to the potassium content of each sample of the formations studied was then calculated. This calculated count was subtracted from the total beta count to obtain the beta emission due to the uranium and thorium series.

The potassium content and a net beta count were determined for 315 samples. The average value for each formation was computed statistically by frequency distribution curves.

Carbon determinations--Carbon was determined by a wet combustion method based on the procedure of CLARK and OGG [1942]. A 150-mg sample was boiled with five ml of a solution containing five per cent H_2SO_4 and five per cent $FeSO_4$ to destroy and remove carbonate carbon. The sample was then oxidized with 25 ml of a solution containing 15 ml of concentrated H_2SO_4, 10 ml of phosphoric acid, and two grams of potassium dichromate. The carbon dioxide thus formed was collected over a three to one glycerine solution containing two per cent KI and transferred by

means of a leveling bulb into an evacuated flask containing a known volume of standard $Ba(OH)_2$ (0.2N). The excess $Ba(OH)_2$ was titrated with standard HCl and the per cent carbon calculated

$$\text{pct C} = [\text{vol. Ba(OH)}_2 - \frac{\text{vol. HCl}}{\text{titer}} \times 0.6 \times \text{N Ba(OH)}_2]/\text{sample weight}$$

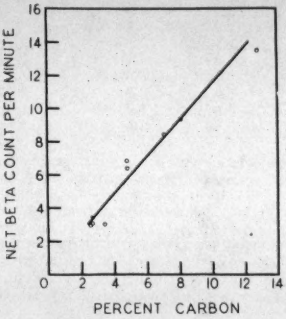


Fig. 2--Relationship between radioactivity and carbon content for nine core sections of the Miocene nodular shale

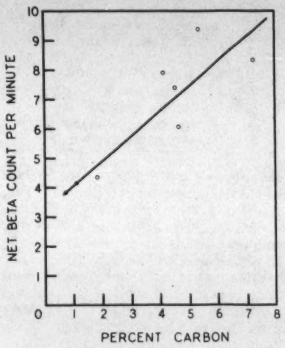


Fig. 3--Relationship between radioactivity and carbon content for eight core sections of the Cherokee shale

Results--One hundred and thirty determinations for organic carbon, potassium, and beta emission were made on the nine cores of Miocene nodular shale. Each core was divided lengthwise into 0.5-cm sections, and determinations (in duplicate) were made on each section. The average carbon content and net beta count for each of the nine cores were then plotted. The resultant points lie close to a straight line (see Fig. 2).

Likewise 105 determinations were completed for the eight sections of the Cherokee shale (see Fig. 3). Deviation of points from the line seems to be somewhat greater than for the Miocene nodular shale, but this core was not all from the same well.

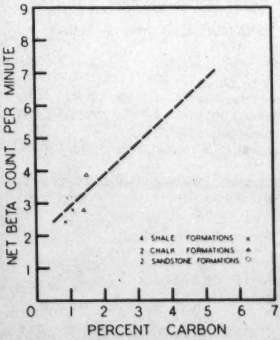


Fig. 4--Relationship between radioactivity and carbon content for eight geological formations

Fewer determinations were made for the other formations.[a] The results for all eight formations are tabulated in Table 2. When the average carbon content and the average net beta count for each formation are plotted, Figure 4 is the result. Although the points in the figure are somewhat scattered, they seem to show a significant linear trend indicated by the dotted line. It should be stressed that the data of Figure 4 represent only a small number of rock types. No generalization is justified nor is any intended for formations other than those studied in the present research.

[a]The use of frequency distribution has been a standard procedure in the work of A.P.I. Research Project 43C in the attempt to establish the mean value and the variability of each of nine sedimentary formations for potassium and for beta emission. The number of determinations necessary for good statistics is judged to be 50 or more on the basis of this experience. Therefore, the upper points on Figure 4 are well established, but the lower points represent less secure values for the formations indicated.

Table 2--Carbon content and net beta count

Formation	Number of determinations	Average carbon content	Average net beta count per minute
		pct	
Miocene nodular shale	130	5.4	6.3
Cherokee shale	105	3.3	5.8
Lower Eutaw shale	12	1.1	2.8
Eagle Ford shale	13	0.93	2.4
Austin chalk	27	1.5	3.9
Selma chalk	15	1.4	2.8
Tuscaloosa sandstone	6	0.97	3.2
Woodbine sandstone	7	0.99	2.4

Summary and conclusions--The carbon content and beta activity due to uranium and thorium have been determined for 315 samples from eight sedimentary geological formations. A detailed study was made of the two shales having the greatest radioactivity, the Cherokee and Miocene nodular shales. The carbon contents of nine cores of the Miocene shale range from 2.56 to 12.8 pct, and the radioactivities from 2.96 to 13.5 beta counts per minute. There is an excellent correlation between the two sets of data, suggesting that there is a concentration of radioactivity in those sediments having higher organic contents. The Cherokee shale shows a similar correlation. This relationship applies not only to samples taken within each individual formation, but also to the eight formations studied in this research, and further suggests that there may be a genetic relationship between uranium, thorium, and carbon content.

Acknowledgments--The authors wish to thank W. L. Whitehead for his counsel and guidance. Thanks must also be extended to students Ann Wilfert, Alfred Wheeler, and Irving Osvar for their assistance in procuring some of the above data.

References

BEERS, R. F., and C. GOODMAN, Distribution of radioactivity in ancient sediments, Bull. Geol. Soc. Amer., v. 55, pp. 1229-1254, 1944.

BELL, K. G., C. GOODMAN, and W. L. WHITEHEAD, Radioactivity of sedimentary rocks and associated petroleum, Bull. Amer. Assn. Petr. Geol., v. 24, pp. 1529-1547, 1940.

BREGER, I. A., Transformation of organic substances by alpha particles and deuterons, J. Phys. Colloid Chem., v. 52, pp. 551-563, 1948.

BREGER, I. A., and V. L. BURTON, The effects of radioactivity on a naphthenic acid, J. Amer. Chem. Soc., v. 68, pp. 1639-1642, 1946.

BURTON, V. L., The effects of radioactivity on oleic acid, J. Amer. Chem. Soc., v. 71, pp. 4117-4119, 1949.

CLARK, N. A., and C. L. OGG, A wet combustion method for determining total carbon in soils, Soil Sci., v. 53, pp. 27-35, 1942.

HOOTS, H. W., A. L. BLOUNT, and P. H. JONES, Marine oil shale, source of oil in Playa del Rey Field, California, Bull. Amer. Assn. Pet. Geol., v. 19, pp. 172-205, 1935.

LEITH, C. K., and W. J. MEAD, Metamorphic geology, Henry Holt and Co., New York, 1915.

LIND, S. C., and D. C. BARDWELL, Chemical action of gaseous ions produced by alpha particles; pt. 9: Saturated hydrocarbons, J. Amer. Chem. Soc., v. 48, pp. 1556-2335, 1926.

SHEPPARD, C. W., and V. L. BURTON, The effects of radioactivity on fatty acids, J. Amer. Chem. Soc., v. 68, pp. 1636-1639, 1946.

TRASK, P. D., Source beds of petroleum, Amer. Assn. Petr. Geol., Tulsa, Okla., 1942.

Department of Geology,
Massachusetts Institute of Technology,
Cambridge 39, Massachusetts

(Communicated manuscript received April 30, 1951;
open for formal discussion until May 1, 1952.)

Transactions, American Geophysical Union Volume 32, Number 6 December 1951

AN ELECTRICAL ANALOGUE FOR THE STUDY OF DIFFUSION PROCESSES WITH INTERNAL GAINS OR LOSSES

C. H. M. van Bavel and A. W. Waltner

(Contribution from the Department of Agronomy, North Carolina Agricultural Experiment Station, and the Department of Physics, School of Engineering, North Carolina State College, Raleigh, N.C. Published with approval of the Director of Research as Paper No. 380 of the Journal Series.)

Abstract--By placing a fairly large number of electrodes in a layer of liquid and with proper boundary conditions an electrical analogue may be constructed that is representative for diffusion of mass or energy through a medium with internal gains or losses. It is shown that the results obtained with such an electrical analogue are in agreement with the ones exacted by a theoretical treatment of such problems for diffusion in one dimension, this being applicable to gaseous diffusion in soils.

It is also shown that this method may be used to obtain information on temperature distribution in cases of heat transfer where heat is being generated or lost in the medium through which it diffuses by conduction. A specific example of such an instance has been examined and numerical values are given.

Introduction--Transfer of energy or mass by diffusion with internal gains or losses occurs both in nature and in engineering. Examples of the first case are the movement of gases through soil, in which oxygen is being consumed and carbon dioxide liberated, or the transfer of oxygen in solution through muscle tissue in which it is being utilized at the same time. An example of the latter case is afforded by heat flow through coils in which heat is generated by the electrical current. The phenomena of mass and energy diffusion are physically different but may mathematically be described in an identical form, and solutions used interchangeably. It can be shown [VAN BAVEL, 1951] that the distribution of partial pressure of gases diffusing through a porous medium (such as soil) is given by

$$\nabla^2 p = - (\beta/D)A \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

in which p is the partial pressure of the gas under consideration, β is the ratio between partial pressure increments and mass increments per unit volume, D is the diffusivity of the gas under consideration through the medium, and A is the rate at which this gas is being liberated or consumed per unit time and volume of the medium. Both A and β/D, the latter of which might be called the specific diffusion impedance, are characteristics of the medium and are, in general, variable in space.

The distribution of temperatures for the similar situation in heat transfer is determined by

$$\nabla^2 t = - G/k \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1a)$$

in which t is the temperature, k the thermal conductivity, and G the amount of heat generated or lost per unit time and unit volume.

Solutions of (1) for a medium bounded perpendicularly to the direction of flow, which occurs in one direction only, have been found by analytical methods [VAN BAVEL, 1951] and it is desirable to verify the results by experimentation. This may be done by utilizing the perfect analogy between the law for diffusion and Ohm's law for electricity in the construction of an electrical analogue that simulates the boundary conditions of the case of interest. For the purpose of examining the type of diffusion that is being considered here, one need not only simulate certain boundary conditions, but also the gain or loss throughout the medium as is apparent from the foregoing.

In this paper a description of the construction and use of such an electrical analogue will be given, and it will be shown that the measured distribution of electric potentials is in close agreement with those predicted by the theory, the latter having been given elsewhere [VAN BAVEL, 1951] for a case of gaseous diffusion. It will subsequently be demonstrated how the presented

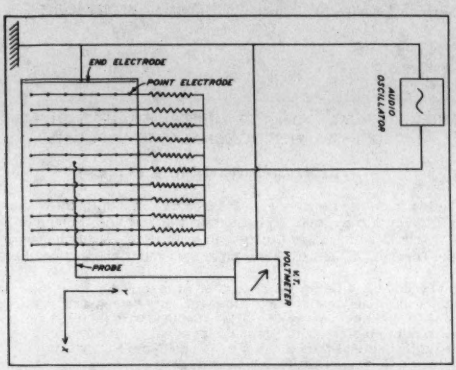


Fig. 1--Schematic circuit of the electrical analogue

method of analogy may be utilized in instances of heat transfer where heat is being gained or lost in the medium through which it is transported by conduction.

Procedure--A tray was constructed from lucite sheet with inside dimensions 20.1 × 30.0 × 2.5 cm. The tray was assembled using commercial windshield sealer. On the underside of the bottom of the tray a sheet of ten-to-the-inch graph paper was pasted, using glyptal. Through the bottom of the tray 11 tiers of seven electrodes each, made of chromium-plated 1/16-inch brass welding rod, were inserted so that each electrode protruded approximately one inch into the tray from its bottom. On the outside of the tray all electrodes on one tier were connected to each other and then were joined to a resistor of approximately one million ohms. Across one end of the tray (see Fig. 1) there was placed an electrode made of chromium-plated brass 1/8 inch thick and one inch high. A photograph of the tray as it was used is given in Figure 2. It will be recognized that the analogue thus described simulates a medium of infinite extent in two directions, vertical and in the y-direction of Figure 1; whereas it is bounded in the third or x-direction by a boundary at which the partial pressure (or temperature) is constant, namely, the electrode at x = 0; and by one that is a barrier to any transfer, this being the opposite end of the tray. The x-distance in the tray corresponds, in the soil, to the depth below the soil surface.

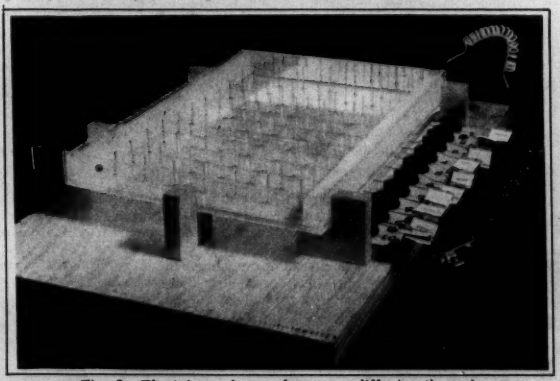


Fig. 2--Electric analogue of gaseous diffusion through porous media with sources, or sinks, in the medium

The circuit with which the measurements of electric potentials in the medium were made is presented in Figure 1. In making these measurements the tray was filled to a known height with tap water or distilled water, or an appropriate mixture of tap water and distilled water. When it was found desirable to study the potential for the case that the medium did not have everywhere the same conductivity, the two parts of the medium were separated by a thin copper sheet. This sheet was connected to the bottom of the tray with some molten paraffin in order to make the separation watertight. The power source used in the circuit was an audio-oscillator (Supreme Instruments Corporation, model 563) which was used at a frequency of 1000 cycles. The terminal voltage of the oscillator under the conditions of the experiment was approximately 50 volts. The measurements of the potential were made with a vacuum-tube voltmeter of which the sensitivity ranged from one millivolt to 100 volts (Hewlett-Packard, model 400-A).

The procedure of experimentation was to insert the probe in the water at a designated distance from the end electrode, this being the plate at $x = 0$ (see Fig. 1), and measure the potential difference between the particular point in the medium and the end electrode. After an appropriate set of potential measurements in the x-direction throughout the medium had been obtained, measurements were made of the potential differences across the 11 resistors of one million ohms in order to determine the rate at which current entered into the conductive medium.

Experimental results--In some preliminary experiments it was found that, using resistors of approximately one million ohms outside of the tray, the voltage across each of these resistors did not vary appreciably between the 11 tiers. (It can be shown by theoretical treatment that the ratio between the value of the outside resistors and the specific resistivity of the medium has to be approximately 1000, in order to find the condition described, allowing for ordinary measuring accuracy.) Thus, it was verified that a nearly equal amount of current entered the conductive medium at every tier of electrodes in the tray. By moving the probe from one side of the tray to the other in the y-direction, parallel to the end electrode, it was also found that the voltage in the y-direction did not change appreciably except very close to the sides of the tray. It was found that this variation could be eliminated almost entirely by decreasing the width of the tray by 1.2 cm on each side. This was accomplished by putting a rim of paraffin against each side of the tray, as shown in Figure 2.

The first case to be tested was the simple one in which the rate of generation (or loss) is constant throughout the medium. For this instance of gaseous diffusion the following formula has been derived [VAN BAVEL, 1951].

$$p = p_0 - (\beta A/D)(-Lx + x^2/2) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

In (2) the symbols have the same meaning as those given in the introduction and, in addition, p_0 is the partial pressure in the atmosphere and the L the extent in the x-direction of the medium in which generation takes place, or the distance from the end electrode plate to the tier farthest from it. The distance from the boundary where $p = p_0$ is designated by x. Making use of the analogy between diffusion and flow of electricity, the appropriate formula for calculating the voltages in the tray becomes

$$V = -(G/C(-Lx + x^2/2) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

in which V is the voltage, G is the rate at which current flows into the medium per unit volume, and C is the conductivity of the medium. In a typical experiment the tap water had a conductivity C of 1.210×10^{-4} mhos cm^{-1}, and the rate of generation G was found to be 6.57×10^{-7} amp cm^{-3}. The latter value was obtained by finding the current through each of the resistors, adding these currents together, and dividing the sum by the volume of the water in the tray. The value for L to be used in the formula was 26.3 cm. Using an appropriate set of values for x, a calculated curve representing the voltage difference between any point in the tray and the top electrode, as a function of the distance x, was drawn, and in Figure 3 this curve is given together with the experimentally obtained voltages. It may be seen that the agreement between experiments and theory is good. This proves that the method of analogy is satisfactory and may be depended upon when an analytical expression for the voltage is not available.

In a second trial the situation was examined where the rate of generation is 0 in an upper layer of certain thickness. For this situation the following formula has been derived [VAN BAVEL, 1951].

$$p = p_0 - (\beta/D)\, A[-(L - b)x + \{(L - b)/2L\}x^2 - 2\Sigma(L^2/n^3\pi^3) \sin(n\pi b/L) + 2\Sigma(L^2/n^3\pi^3) \sin(n\pi b/L) \cos(n\pi x/L)] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

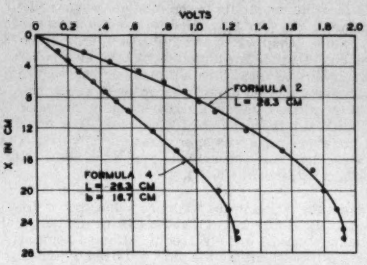


Fig. 3--Theoretical curves for the electric potential as a function of the distance and experimentally obtained values, for two different cases of a homogeneous medium

where n = 1, 2, 3, ...

In this formula the symbols have the same meaning as before. The additional symbol b stands for the thickness of the overlying layer without generation. Denoting the bracketed part of (4) by the symbol F, the following expression is obtained from which the theoretical potentials may be calculated.

$$V = -(G/C)F \quad \ldots\ldots\ldots\ldots (5)$$

Values of F have been charted elsewhere [VAN BAVEL, 1951].

In the corresponding experiment L was 26.3 cm, b was 16.7 cm, and the tiers within 16.7 cm of the electrode plate were disconnected. In Figure 3 the curve representing the voltage as a function of the distance x, as computed from the above formula, is presented together with the values for the voltage that were obtained by experimentation. It may be seen that also in this case the agreement between theory and experiment is good.

The third case to be examined by the present method of electrical analogy is the one in which the rate of generation is uniform throughout the medium, but in which two layers of different specific diffusion impedance are superimposed on each other. The formula giving the partial pressure in such case is [VAN BAVEL, 1951]

$$p = p_0 - (\beta/D)A\,[-\left\{(L + (m-1)b)/m\right\}x + \left\{(L + (m-1)b)/2mL\right\}x^2 + \left\{(2m-2)/m\right\}\Sigma(L^2/n^3\pi^3)\sin(n\pi b/L) - \left\{(2m-2)/m\right\}\Sigma(L^2/n^3\pi^3)\sin(n\pi b/L)\cos(n\pi x/L] \quad \ldots\ldots\ldots\ldots (6)$$

where n = 1, 2 3, ...

In this formula the symbols have again the usual meaning, and, in addition, m is the ratio between the specific diffusion impedance of the top layer (x = 0 to 16.7) and the bottom layer (x = 16.7 to 26.3); and b is the distance of the discontinuity. For computing the potentials we may use

$$V = -(G/C)F \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

in which C now stands for the conductivity of the top layer of the medium in the tray and F is the value of the bracketed part in (6), the value of which has been tabulated in graphical form [VAN BAVEL, 1951].

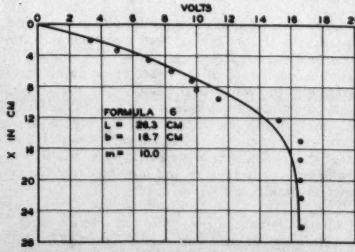


Fig. 4--Theoretical curve for the electric potential as a function of the distance and experimentally obtained values for an inhomogeneous medium

In the case of the corresponding experiment, L was again equal to 26.3 cm, b to 16.7 cm, the conductivity of the top layer 5.43×10^{-6} mhos cm^{-1}, and the conductivity of the bottom layer 5.43×10^{-5} mhos cm^{-1}. The appropriate conductivities were obtained by mixing distilled water and tap water. In Figure 4 the theoretical curve is presented with experimentally obtained values and here again the agreement between theory and experiment is in general good, although a discrepancy seems to occur above the discontinuity in the medium.

The validity of this method of electrical analogy being proved by the foregoing experiments, an example will next be given of how this procedure may be used to obtain information in a case which is typical of situations

where analytic solutions are difficult to obtain or not available at all. The application will be made to a situation in heat transfer. Experiments with electrical analogues in heat transfer, where problems arise with media in which heat is being generated or lost, seem not to have been performed in the past and for this reason this application is presented. JAKOB [1949] mentions investigations with simulating electrical networks, which are essentially different from the presented method and more complicated.

Suppose there exists a medium of infinite expanse in x- and y-direction and of unit thickness in the z-direction (the xy faces at $z = 0$ and $z = 1$ are considered to be insulated, that is, $\partial t/\partial z = 0$; in this way the solution will be valid for a medium infinite also in the z-direction), in which heat is being generated at a rate of G calories per cm^3 per second and through which medium tubing for cooling purposes is running in the z-direction at regular inter-distances. The problem to be solved is then finding the temperature at any point in the medium when the temperature at the surface of the cooling tubes is known. If we assume that in the medium under consideration the cooling tubes are spaced equally in the x-direction, namely, seven inches, and that in the y-direction they are spaced 12 inches, and further that their diameter is one inch, this problem may be solved using the tray that was described before. In order to do so every individual electrode that is protruding into the liquid is connected to a resistor of a large value. In this case resistors of 760,000 ohms were used. The plate electrode that was mentioned before is taken out and exactly in the center of the tray there is placed a cylindrical electrode of brass one inch in diameter, which is grounded. The "point" electrode in the center of the tray is also removed. The method of measurement is exactly the same as in previously described experiments. In contrast to the previously discussed cases, the value of the factor F may be computed from the experimentally obtained voltages. These F-values then in turn may be used to calculate the temperature at any point in the medium using

$$t = t_0 - (G/k)\,F \qquad (8)$$

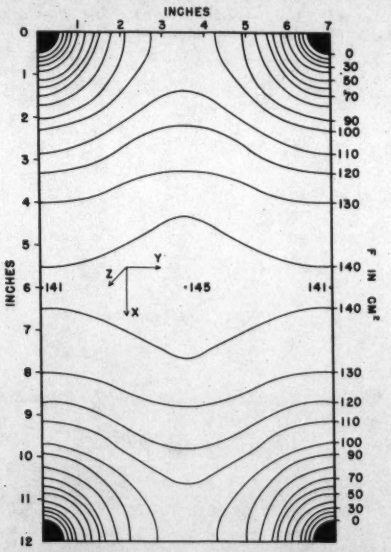


Fig. 5--Temperature distribution in a two-dimensional field between four cooling tubes, heat being uniformly generated in the field, as obtained from an electric analogue

in which t is the temperature at any point in the medium, t_o is the temperature at the surface of the cooling tubes, F is the factor mentioned above, G is the number of calories generated per cubic centimeter per second, and k is the thermal conductivity in cal sec^{-1} cm^{-1} $°C^{-1}$. In Figure 5 the values of F, as they are found in this experiment, have been charted in a representative section of the medium in which transfer of heat takes place. Since the unit of length that was used everywhere was cm, the dimension of the factor F is cm^2.

The values of F that are given here can be used not only for a case where the medium has exactly the dimensions as the one examined here, but also when those same dimensions are all proportionally larger or smaller. In such a case the values of F may be found by multiplying the ones that are given here by the square of the ratio of the dimensions. If, however, the medium has a different shape, a different model must be constructed. In engineering practice sometimes instances occur that are related to the example given here; for instance, the generation of heat by induction, cooling of setting concrete structures, or cooling a nuclear reactor. It should be pointed out here that the last problem discussed was one in two dimensions whereas the first three were problems in one dimension only. It is evident that models of any shape in two dimensions may be set up for solution with the present method, and one may even envisage three-dimensional models.

References

JAKOB, M., Heat transfer, John Wiley, 1949.
VAN BAVEL, C. H. M., A soil aeration theory based on diffusion, Soil Science, v. 72, pp. 33-46, 1951.

Department of Agronomy,
North Carolina State College,
Raleigh, North Carolina

(Manuscript received March 15, 1951, and, as revised, June 4, 1951;
presented at the Thirty-Second Annual Meeting, Washington, D. C.,
May 1, 1951; open for formal discussion until May 1, 1952.)

Transactions, American Geophysical Union Volume 32, Number 6 December 1951

EVALUATION OF THE CRITICAL REGIME IN STRATIFIED FLOW

A. Craya

Abstract--A fundamental role in the study of flow in open channels is played by the concept of the critical regime. This concept has recently been generalized by Rossby for gravity currents due to density stratification, the implications of which should provide a better understanding of the distribution of winds, oceanic currents, and flow due to density stratification in general.

The purpose of the present paper is to interpret this generalized concept from the hydraulics point of view. Consideration of the momentum principle and of the energy principle permits the formulation of two integral expressions for the cross section of a stratified current, the value of which can only decrease. These integrals nevertheless have a minimum value which is attained for a certain thickness of the current and for a certain velocity distribution, which by definition represent the critical regime. Critical regimes obtained by the two foregoing principles are not identical, though very nearly so.

Concerning the shape of the critical distribution of velocity, the following cases are distinguished: (a) For a surface current without any restriction on the displacement of the topmost layer, the velocity increases from zero at the interface to a maximum at the free surface; (b) for a surface current of which the topmost streamline is restricted to a condition like constancy of elevation, there is a maximum velocity some distance under the free surface.

Introduction--The important role played by the notion of the critical regime in the hydraulics of open channels is well known; from the whole gamut of depths at which a given discharge can take place on a fixed bottom, the momentum principle and the energy principle lead to the definition of the critical state for two-dimensional flow as being the condition at which the depth of flow is twice the velocity head. This notion governs to a great extent the development of backwater curves; in a horizontal channel, for example, the flow necessarily tends towards the critical state.

Oceanic currents resulting from the action of gravity on layers of lighter liquid overlying a body of motionless water are in certain respects comparable to flow in open channels, with, however, the differences and complications resulting precisely from the density stratification. A generalization of the notion of the critical regime for these currents recently proposed by Rossby [1951] seems destined to render valuable service in various problems of hydraulics, oceanography, and meteorology [see also CRAYA, 1951].

In this paper, we shall seek to give an intuitive and simple presentation of this generalization of the critical regime starting from the classical notion of hydraulics. Using, together with the momentum principle considered by Rossby, the equally important energy principle, we shall find that, contrary to the similar case in hydraulics, these two viewpoints yield close but not identical results. We shall note, finally, the modifications imposed on the critical state when the free surface of the current is subjected to the condition of remaining horizontal.

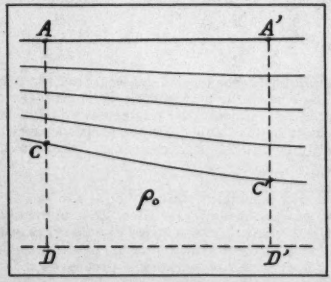


Fig. 1--Gravity currents

Free-surface gravity currents--Fig. 1 shows schematically the flows which we propose to study in this paper. Assume that n layers of constant density are flowing over a body of water of density ρ_0, motionless beyond a certain depth; the density of each layer is smaller by $\Delta\rho$ than that of the one immediately below. This discontinuous variation of the density is merely a means of representing simply and in a geometrical manner the results that we have in view; by increasing indefinitely the number of layers, it is easy to arrive at a continuous density variation.

The flow is considered two-dimensionl (in the plane of the figure); consequently, the discharge of each elementary layer is constant; let Δq_i be the

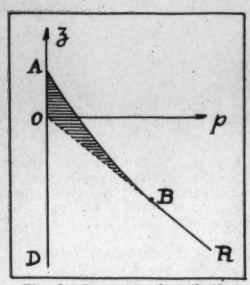


Fig. 2--Pressure distribution

discharge for the layer numbered 1.

We shall suppose also that, as in the hydraulics of open channels, the curvatures of the different streamlines (and thus also the vertical accelerations) are extremely slight, so that the distribution of pressures will be hydrostatic along each vertical section.

We shall represent the distribution of pressures at different sections on the same graph Opz (Fig. 2). If the liquid of density ρ_0 existed alone, the free surface would be at 0. As this water has been assumed motionless from a certain depth down, the different points 0 lie on a horizontal, which in the following treatment will always be taken as the reference plane. The possible distributions of pressure are then lines AB tangent to the fixed line OR.

Application of the momentum and energy relationships--Consider the portion of the current included between the two vertical sections AC and A'C'.

(1) Let $\mathbf{F}$, $\mathbf{F}'$, and Φ be the horizontal components of the forces acting, respectively, on the sections AC and A'C' (action of the liquid to the left on the liquid to the right) and on the lateral surface CC' (action of the lower liquid on the upper liquid). Let, on the other hand, $\mathbf{M}$ and $\mathbf{M}'$ be the horizontal component of the flux of momentum across AC and A'C'. The momentum theorem then gives in all rigor

$$\mathbf{F}' + \mathbf{M}' = \mathbf{F} + \mathbf{M} + \Phi$$

The forces $\mathbf{F}$, $\mathbf{F}'$, and Φ are due in part to pressure and in part to viscous and turbulent stresses. (For a turbulent flow the theorem of momentum is applied to the mean flow.) Separating in each term the part due to the pressures and calling the remaining parts $\mathbf{f}$, $\mathbf{f}'$, and ϕ, respectively, the above equality is written

$$\int_{C'A'} pdz + \mathbf{M}' + \mathbf{f}' = \int_{CA} pdz - \int_{CC'} pdz + \mathbf{M} + \mathbf{f} + \phi$$

If we consider now a portion CDC'D' of the lower liquid limited by the horizontal DD', the hydrostatic pressure distributions in this region require that

$$\int_{D'C'} pdz = \int_{DC} pdz + \int_{CC'} pdz$$

By adding these relations we see that the integrals of the pressures along DA and D'A' are introduced; as these have in common the triangle ORD, it is sufficient to consider only the variable part, which is the cross-hatched area AOB. Denoting this area by A and the momentum flux still by $\mathbf{M}$, we have

$$(\mathbf{A}' + \mathbf{M}') - (\mathbf{A} + \mathbf{M}) = \phi + \mathbf{f} - \mathbf{f}'$$

If the lighter liquid entrains the motionless lower liquid, the part of the tangential stresses composing ϕ must be essentially negative; on the other hand, the part of the normal stresses which enters into ϕ and the term $\mathbf{f} - \mathbf{f}'$ disappears for a quasi-uniform regime; we can then admit that the hypotheses of quasi-hydrostatic pressure distributions imply also the preponderance of the negative friction term, and hence that the quantity $\mathbf{P} = \mathbf{A} + \mathbf{M}$ can only decrease with distance downstream.

(2) Let us apply now to the mass ACA'C' the energy principle. This principle can be expressed, if we consider the mean velocities for the general case of a turbulent flow, in the following manner: The work of all the external forces (gravity and stresses at the periphery) is equal to the variation of the kinetic energy of the mean flow plus the dissipation of the mean motion and the energy transferred to the turbulent movement. If we separate the work of pressures and of gravity and the variation of kinetic energy, this relation can be written

$$\int_{\Sigma} (p + \rho gz + \rho V^2/2)\, dq = N + R - D - T$$

where N and R are the work of the Navier and Reynolds stresses, respectively, at the periphery, D is the dissipation of the mean flow, T the transfer to the turbulent flow, and dq the discharge coming out across an element of surface of contour AC C'A'.

As previously, we can suppose that in the work of the stresses the term giving the friction along CC' outweighs the others and renders negative the sum of N + R. From this it follows that the integral of the first member is negative. As it reduces itself to the difference of integrals taken along A'C' and AC, the expression

$$I = \int (p + \rho gz + \rho V^2/2)\, dq$$

which can be called the energy flux across AC, decreases with distance downstream. As the current is supposed to change very gradually, in the future we will let V be represented by the horizontal component u of the velocity.

It should be remarked that the two results which we just obtained have nothing of the nature of self-evident truths. Their validity depends on the nature of the currents we are studying.

As in the hydraulics of open channels we shall now show that the quantities P = A + M, which we shall call "thrust," and I, which shall denote energy flux, cannot decrease below a certain value; the total thickness of the current and the distribution of the velocities which affect this minimum shall define the critical state.

Conditions for the minimum of thrust--Let us focus our attention on one of the layers numbered i of thickness Δz_i and let us consider a new state of the current in which this layer has undergone a diminution of its thickness by the amount $\delta \Delta z_i$ (Fig. 3).

The new pressure distribution can be obtained by translating the portion AI above the layer i by the amount II'. Naturally, to retain the same axes of reference, it then would be necessary to apply to the new distribution A'I'JB a translation O'O. However, as we are interested here simply in the variation of area between AOB and A'O'B', it will be more convenient to neglect this last displacement. Inspection of Figure 3 then immediately shows that the decrease of area A is represented by the surface OO'm'm, since the portions of area AmI and A'm'I' above the straight line IM result from a translation and are equal.

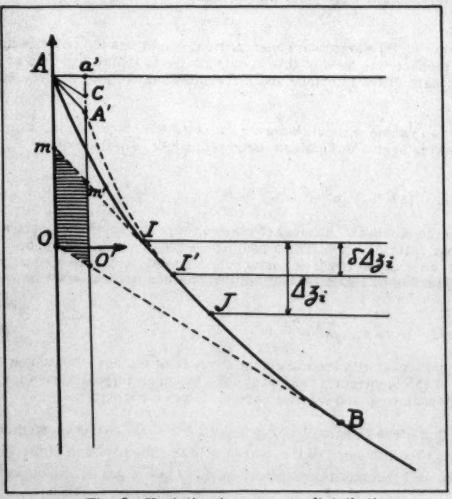


Fig. 3--Variation in pressure distribution

The point m represents the piezometric level of the layer i, that is, the fictitious free surface which would have corresponded to the hydrostatic distribution of pressures in this layer. If, as we have assumed, we take for the horizontal reference plane of elevation the piezometric level O of the lower motionless liquid, we have

$$Om = (p/\rho g + z)_i$$

Moreover, the law of hydrostatic pressure distribution applied to the triangle AA'a' shows that

$$Aa' = \rho_i g\, \delta \Delta z_i$$

Hence, the decrease of area A is, neglecting terms of higher order than $\delta\Delta z$,

$$\delta A = (p_i + \rho_i g z_i)\ \delta\Delta z_i$$

Let us pass now to the variation of momentum flux across the current. The only term which has varied is evidently the momentum flux M_i across the layer i

$$M_i = \rho_i u_i^2\ \Delta z_i = \rho_i\ (\Delta q_i^2/\Delta z_i)$$

Again neglecting higher-order terms, the decrease of momentum flux for a diminution $\delta\Delta z_i$ in the thickness of the layer can be written

$$\delta M_i = -\ \rho_i\ (\Delta q_i^2/\Delta z_i^2)\ \delta\Delta z_i = -\ \rho_i\ u_i^2\ \delta\Delta z_i$$

We deduce from this for the variation of the thrust A + M

$$\delta(A + M) = (p_i + \rho_i g z_i - \rho_i u_i^2)\ \delta\Delta z_i$$

This reasoning being valid for any of the n layers composing the current, it follows that the condition for the minimum thrust can be written for any number of these layers, and in particular for a continuous distribution as

$$\rho u^2 = p + \rho g z \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

This is the fundamental law of the critical regime as regards the thrust. Let us add, however, that it necessarily supposes that all the parameters Δz_i are independent; in other words, that the thickness of each of the layers can vary freely. This will be the case if no particular restriction or condition is imposed on the vertical displacement of the free surface of the current at A. We shall come back again to this remark.

It is easy to see that (1) determines completely the total height of the current and the velocity distributions. Using again the language of layers, we see that, in fact, if we begin arbitrarily from a point B (Fig. 3) and give the discharges of the different layers, we determine successively all their thicknesses. When we arrive at the last layer, however, there is no reason why we should come up with a zero pressure; this last condition, p = 0 at the surface, thus completes the definition of the critical state.

Written in the form $u^2/g = p/\rho g + z$, (1) shows that under critical conditions the velocity head of each layer is proportional to the piezometric head of this layer relative to that of the fluid at rest. The velocity begins then from zero at the interface and increases constantly to the free surface.

As examples we shall consider two cases, without, however, showing the calculations. For a single layer of density $\rho_0 - \Delta\rho$ flowing over a motionless liquid of density ρ_0, the critical height is given by

$$\Pi = (\Delta\rho/\rho_0)\ gh^3/q^2 = 1$$

and this case is evidently similar to the horizontal channel of classical hydraulics with simply a gravity reduced at the interface in the ratio $\Delta\rho/\rho_0$. For a continuous density distribution between ρ_0 at the lower interface and $\rho_0 - \Delta\rho$ at the free surface, and a total discharge q equally distributed among all layers corresponding to a same density difference, the critical state is given by

$$\Pi = (\Delta\rho/\rho_0)\ gh^3/q^2 = 6$$

and the distribution of velocities is parabolic with the maximum at the free surface. In the general case of any law of distribution of the elementary discharges the parameter Π continues for dimensional reasons to govern the phenomenon and only its numerical value changes.

Condition for minimum energy flux--The integral $I = \int (p + \rho g z + \rho u^2/2)\ dq$ can be studied in an analogous manner by considering the influence of the decrease in thickness of one of the layers numbered i. We shall distinguish in I the part representing work, $\int (p + \rho g z)\ dq$, which we shall denote by T, and the kinetic energy flux, $\int \rho u^2/2\ dq$, which we shall call C.

But now the evaluation of the variation of T necessarily requires that the new distribution of pressures be referred to the fixed axes AOB, which can be easily accomplished by applying to the distribution A'OB a translation O'O. Finally, the new distribution of pressure, after the contraction of the layer i by the amount $\delta\Delta z_i$, is deduced from the old one by (a) translation of the part AI by the amount AA' + O'O and (b) a translation of the part I'B by O'O.

The effect of such translations on the term T can be best seen by resolving them into horizontal and vertical translations. A downward vertical translation by the amount ℓ diminishes each term $(p + \rho gz)$ by $\rho g \ell$; a horizontal translation to the left of magnitude m diminishes each term $(p + \rho gz)$ by m.

As far as the part AI is concerned, we see immediately that the resultant translation AA' + O'O is vertical (by drawing AC parallel and equal to OO') and that its value $\ell = CA'$ results from

$$Aa' = \rho_i g\, a'A' = \rho_0 g\, a'C$$

from which

$$a'C = (\rho_i/\rho_0)\ \delta\Delta z_i \qquad \text{and} \qquad CA' = (1 - \rho_i/\rho_0)\ \delta\Delta z_i$$

The decrease of T relative to AI then can be written, denoting by ρ_s the density at the free surface,

$$\delta_1 T = g\,(1 - \rho_i/\rho_0)\ \delta\Delta z_i \int_{\rho_s}^{\rho_I} \rho\, dq$$

The translation CA to be imposed on the portion I'B can be resolved into a vertical translation $Ca' = -\,(\rho_i/\rho_0)\ \delta\Delta z_i$ (measured positively downward) which contributes to the variation of T the amount

$$\delta_2 T = -\,g\,(\rho_i/\rho_0)\ \delta\Delta z_i \int_{\rho_{I'}}^{\rho_0} \rho\, dq$$

and a horizontal translation a'A which will diminish T by

$$\delta_3 T = g\,\rho_i\ \delta\Delta z_i \int_{\rho_{I'}}^{\rho_0} dq$$

Upon adding these three terms, we obtain for the total decrease T (by letting ρ_i absorb ρ_I and $\rho_{I'}$)

$$\delta T = g\,[\int_{\rho_s}^{\rho_i} \rho\, dq - (\rho_i/\rho_0) \int_{\rho_s}^{\rho_0} \rho\, dq + \rho_i \int_{\rho_i}^{\rho_0} dq]\ \delta\Delta z_i$$

or, alternatively, integrating by parts and denoting by dq the discharge between the free surface and a lower streamline of density ρ,

$$\delta T = -\,g\,[\int_{\rho_s}^{\rho_i} q\, d\rho\ - (\rho_i/\rho_0) \int_{\rho_s}^{\rho_0} q\, d\rho\,]\ \delta\Delta z_i$$

We still have to evaluate the influence of the contraction of one layer on the kinetic energy flux C, which is rather easy because only C_i corresponding to the layer i is modified. Thus,

$$C_i = (\rho_i u_i^2/2)\Delta q_i = \rho_i\, \Delta q_i^3/2\Delta z_i^2$$

and

$$\delta C_i = -\,\rho_i u_i^3\ \delta\Delta z_i$$

Finally, by setting equal to zero the variation of the energy flux of any layer, we obtain the new condition for the critical regime

$$\rho u^3 = g\left[(\rho/\rho_0)\int_{\rho_s}^{\rho_0} q\,d\rho - \int_{\rho_s}^{\rho} q\,d\rho\right] \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

The distribution of discharges among the different layers (that is, the function q (ρ)) being given, (2) defines directly the critical distribution of velocities, which corresponds again to a zero velocity at the interface and a maximum at the free surface; from this and from $dq = -u\,dz$ we can deduce the distribution of the thicknesses of the different layers and the critical depth.

We shall give again as examples, but without going into the calculations, the result corresponding to a single layer of density $\rho_0 - \Delta\rho$, where ρ_0 is the density of the fluid at rest, and that corresponding to a continuous density distribution with uniform distribution of discharge among the different layers. The first case is characterized by

$$\Pi = (\Delta\rho/\rho_0)\,gh^3/q^2 = 1$$

and the second by $\Pi \approx 4.2$.

We can see that, whereas the two viewpoints of the momentum principle and the energy principle lead to the same result for the case of a single layer, just as in the hydraulics of open channels, this is not so for several layers, although the results are comparable.

Case of an imposed condition at the free surface--The conditions of the minimum obtained in the preceding paragraphs are necessarily based on the assumption that there is no restriction imposed on the displacement of the free surface. Is such always the case? This question comes up, for example, if we think of a current of limited width bordered laterally by a liquid at rest. It is difficult to imagine in such a case that appreciable differences in level can be established between a gravity current and the surrounding liquid. On the other hand, there is nothing which proves that the simple two-dimensional scheme studied previously applies perfectly to the problem of oceanic currents with freedom of lateral movement. Without deciding the question, which evidently requires more research, we would like to show here simply the modifications which the critical regime will undergo due to such a condition imposed on the free surface.

If we imagine again that the current is divided into layers, we see that their thicknesses Δz_i are no longer entirely free if such a condition as

$$OA = a = \text{constant} \quad \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

is imposed.

To obtain the minimum of the thrust or of the energy flux for all states which verify (3), we must look for the minimum of these expressions increased by the amount ka, in which k is a parameter which shall be determined later by means of (3). In other words, we must add to (1) and (2) a term $k\,\delta a/\delta\Delta z_i$. We see from Figure 3 that, as the thickness of a single layer is decreased by $\delta\Delta z_i$, the variation of a is $\delta a = CA' = (1 - \rho_i/\rho_0)\,\delta\Delta z_i$.

The condition for the minimum thrust is then given by

$$\rho u^2 = p + \rho gz + (\rho - \rho_0)\,g\alpha \quad \ldots\ldots\ldots\ldots\ldots\ldots (1a)$$

and that of the energy flux by

$$\rho u^3 = g\left[(\rho/\rho_0)\int_{\rho_s}^{\rho_0} q\,d\rho - \int_{\rho_s}^{\rho} q\,d\rho + (\rho - \rho_0)\beta\right] \ldots\ldots\ldots\ldots (2a)$$

where α and β are parameters determined by (3).

These new conditions show that the critical distribution of velocities begins again with a zero velocity at the lower interface, but attains this time a maximum some place below the free surface; this is a rather remarkable consequence of the restriction imposed on the displacement of the free surface.

Conclusions--In open-channel hydraulics the elementary concept of the critical regime is of importance for two reasons. On the one hand, it defines certain minimum conditions of flow in terms of fundamental principles of mechanics. On the other hand, it provides a means whereby the various aspects of flow in channels may be interpreted.

The extension of this concept to include the case of gravity currents due to density stratification accomplishes the same dual purpose. Not only is it of theoretical interest, but it appears to be a valuable guide for the general study of such phenomena, in that it indicates the sense of development of these currents in the direction of the critical regime.

As is true of the elementary concept, its extension must be considered as only an element of a more complete treatment including the effect of friction, a theory which unfortunately appears much more difficult to establish for stratified flow than for that of a homogeneous liquid.

References

CRAYA, A., Critical regimes of flows with density stratification, Tellus, v. 3, no. 1, pp. 28-42, Feb. 1951.

ROSSBY, C.-G., On the vertical and horizontal concentration of momentum in air and ocean currents, I. Introductory comments and basic principles, with particular reference to the vertical concentration of momentum in ocean currents, Tellus, v. 3, no. 1, pp. 15-27, Feb. 1951.

Iowa Institute of Hydraulic Research,
State University of Iowa,
Iowa City, Iowa
(On leave from Etablissements Neyrpic and University of Grenoble, France.)

(Manuscript received May 1, 1951; presented at the Thirty-Second Annual Meeting, Washington, D. C., April 30, 1951; open for formal discussion until May 1, 1952.)

Transactions, American Geophysical Union Volume 32, Number 6 December 1951

ON THE ORIGIN OF RIVER MEANDERS

P. Wilh. Werner

Abstract--The present paper deals with the origin of river meanders. It is believed that the regular pattern characteristic of meandering, and especially the more or less constant nodal distance between bends of a given river stretch, are closely connected with transverse oscillations of the stream. The study aims at correlating in a simple formula the main factors governing the initiation of meanders. As far as possible, the theory is checked against observations on natural and model streams.

Introduction--The meandering of rivers is here referred to as the continually changing sinuous course developed by silt-bearing streams in erodible alluvial sediments. As a matter of distinction, the earlier meander stages, that is, before the development of loops, may be denominated serpentines [de GEER, 1911; SCHOKLITSCH, 1930]. The whole process of meandering, inclusive of serpentines, has received considerable attention in the past, and much has been written to explain its appearance, at first maybe from a geographical angle, but later also from geophysical and engineering points of view. Whereas the development in the later stages of meander formations is fairly well known through studies of alluvial rivers, no conclusive theory exists as regards the embryo of the process. As far as the writer is aware, the various hypotheses bearing on the subject ascribe the initiation and development of serpentines and meanders to one of the following causes: (1) the Earth's rotation [von BAER, 1860]; (2) local disturbances, such as variable bank material, obstructions, and tributary confluences [PENCK, 1894; DAVIS, 1903; HEDIN, 1904; VUJEVIC, 1906]; (3) excessive energy of the stream [JEFFERSON, 1902; SCHOKLITSCH, 1930]; (4) changes in river stage [RUSSEL, 1936]; (5) forced oscillations of the flow [HAMBERG, 1908; de GEER, 1911; EXNER, 1919].

Geographical investigations [de GEER, 1911, p. 177] show that the theory involving the Earth's rotation can be left out of consideration in a discussion of the fundamentals of meandering. As regards the other four theories, each one of them probably contains part of the truth with respect to the occurrence of meanders, but in their present form they all fail to explain the conspicuous sinuous pattern with a certain nodal length of the bends.

An extensive laboratory study executed at the U. S. Waterways Station in Vicksburg presents a very valuable contribution towards the solution of the meander problem. One of the most important findings in these tests, as described in a Report by the Mississippi River Commission [TYLER and FRIEDKIN, 1945], is that bank erosion constitutes a sufficient (and necessary) requirement for the occurrence of meandering in alluvial rivers. Similar tests have also been executed at the Imperial College in London; according to a letter received by the writer, the results of these experiments agree on the whole with those of the Vicksburg tests.

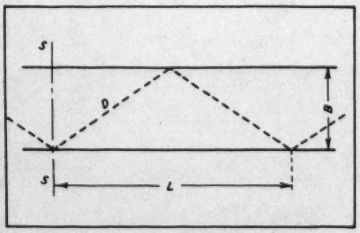


Fig. 1--Diagrammatic sketch of a length of straight channel

Present theory--The following general terminology will be used in the paper, with supplementary symbols given in the text.

- L = meander length = twice the nodal distance (see Fig. 1)
- B = width of river channel
- h = depth of river channel
- T = period of oscillation
- Q = discharge
- v = stream velocity
- $w = \sqrt{gh}$
- g = acceleration of gravity
- $v_c = w/\beta$ = critical serpentine velocity (see text)
- β = a coefficient (see text)
- m = roughness coefficient in Manning's open-channel formula

As stated in the introduction, several authors assume that the initiation of meandering is caused by oscillations of the water. Considering the easiness with which an enclosed water body is subject to oscillations, there should be no doubt that transverse waves play an important role in the formation of serpentines and meanders. However, the significance of this phenomenon in natural rivers seems to have been clearly realized only in recent years [MATTHES, 1941].

Assume that in a straight channel, as shown diagrammatically in Figure 1, each vertical sheet of water passing a certain section s - s be subject to transverse oscillations due to some local impulse or disturbance (tributary confluence, sand bar caused by bank erosion, or the like). The slowest mode of the oscillation, combined with the stream velocity, will then appear as an asymmetric wave, the crests (and troughs) of which, when traveling downstream, fall alternately on the left and right banks of the stream. The first serpentine bend will form the disturbance for the next bend, and so on; noting that the motive power is constituted by the excessive energy of the river, it may be visualized that the wave train will continue downstream, more or less irrespective of possible damping effects.

In the mathematical treatment of our theory there will appear a new concept, which may be denominated "critical serpentine velocity." Let us for a moment consider a comparatively shallow trough closed at both ends. The period of pure seiches in the trough may be written, for the slowest mode,

$$T = \alpha d/w \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

in which d denotes the length of the trough, α is a coefficient dependent on the form of section, and the other notation as given above. For a rectangular section we have $\alpha = 2$ [LAMB, 1945, p. 265] and for a parabolic section [EXNER, 1919, p. 1459] we have $\alpha = \pi/\sqrt{3} \sim 1.82$. In most practical cases we may with sufficient accuracy put $\alpha = 2$, so that (1) takes the form

$$T = 2d/w \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

In this equation no account is taken of sediment content or turbulence. However, in the meandering process an important role is played by the sediment load, and especially the bed load, which latter "drags along the bottom by rolling and saltation, or which, in the case of streams transporting very fine materials, takes the form of a dense mass moving in semi-suspension just above the bed" [MATTHES, 1941]. It is now postulated that the bed load, mainly due to its internal friction, materially prolongates the period of the skew oscillations of the stream. This postulate is supported by small-scale experiments on debris-laden water; and, as will be demonstrated subsequently, the theory based on it shows a satisfactory qualitative agreement with actual observations on meandering streams. The effect of the sediment content is probably much strengthened by the turbulence of the water.

To allow for the combined effect of the bed-load, the turbulence, and possibly also other causes, we introduce in (2) a coefficient $\beta \geq 1$, thus

$$T = 2d/v_c \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

in which the critical serpentine velocity enters as

$$v_c = w/\beta \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Turning again to the stream in Figure 1, it seems plausible, for the purpose of the investigation, to assume that the length governing the period is the diagonal distance D. Introducing D = d in (3), we obtain

$$T = \sqrt{4B^2 + L^2}/v_c \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

Further we have, obviously,

$$T = L/v \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

Combining (5) and (6), we obtain after some transformations

$$L = 2Bv/\sqrt{v_c^2 - v^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

It should be noted that (7) refers to the initiation of a serpentine in a straight channel. Although in this study we are not concerned with the successive development (widening) of the serpentines, it is worth observing that during this process the transverse oscillations are evidently influenced by an increasing width greater than the width B of the river, and probably also by other factors such as the centrifugal force in the bends. So far, we account for this time variation by substituting for B a variable quantity $B_t \gtrless B$, thus

$$L = 2B_t v/\sqrt{v_c^2 - v^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

in which the value $B_t = B$ corresponds to the initial oscillation attack on the straight stream banks.

For the friction losses in the stream we may apply Manning's well-known formula for the flow in open channels. Noting, further, that for natural rivers the hydraulic radius may be taken equal to the mean water depth, we have

$$v = m\, r^{2/3} s^{1/2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

and

$$Q = m\, Br^{5/3} s^{1/2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (10)$$

Introducing (9) in (8), we obtain

$$L = 2B_t [-1 + g/(\beta^2 m^2 s\, r^{1/3})]^{-1/2} \quad \ldots\ldots\ldots\ldots\ldots (11)$$

which, in combination with (10), and with $B_t = B$, demonstrates the main factors governing the initiation of serpentines. These factors may be listed as (1) bed material (bank erosion, prerequisite); (2) slope, s; (3) silt content, β; (4) hydraulic properties of river channel (hydraulic radius r, width B, roughness m); and (5) hydrologic conditions (discharge Q).

This list is in principal accordance with the present general conception or meandering [MATTHES, 1941], as based on studies of alluvial rivers. There seems to be no justification whatsoever for grading the importance of the various factors relative to each other. Judging from the above derivations, they all have a great bearing on the initial formation of serpentines.

Theory versus observations--The foregoing is an attempt to coordinate in a simple formula certain basic factors relating to the initial stages of meandering. It is of interest to investigate how far the theory presented is compatible with what is actually known about the behavior of meandering streams, in nature or in models.

The formulas do not contradict that bank erosion is a prerequisite for meandering. For $v = 0$, we obtain $L = 0$, as it should be. Further, when $\beta \to 0$ implying a negligible bed load, (11) yields $L \to 0$, that is, no meandering occurs. This is in complete agreement with the present knowledge of meandering, according to which the bed load, whether derived from bank caving or from other sources, is of primary importance to the process.

For $v = v_c$ Eq. (8) gives $L = \infty$, implying that the straight channel is maintained, and for $v > v_c$ the value of L becomes imaginary. In principle, this agrees with the observation that true meandering does not occur in rivers if the velocity exceeds a certain value, which then would correspond to the critical serpentine velocity. Further, from (11) we find that L generally increases when the slope increases, as also clearly verified by the Vicksburg experiments [TYLER and FRIEDKIN, 1945, p. 9]. When the slope exceeds a certain value, however, the denominator in the formula becomes zero or imaginary. This is in accordance with the fact [de GEER, 1911, p. 104] that true meandering does not occur in swift mountain streams. The irregular and angular windings in such streams are of quite another nature than the comparatively smooth serpentine and meander bends. It is important to distinguish the two classes of windings from each other.

Meandering streams are notoriously shallow [see, for instance, MATTHES, 1941, p. 634]. From (11) we may also infer that meandering cannot occur if the water depth exceeds a certain critical value for which the denominator in the formula becomes zero or imaginary. However, in case of extremely shallow cross sections the denominator becomes very large, and the formula may then yield values of L so small that the formation of serpentines is imperceptible. It is possible in this way to explain the existence and persistence of reaches as observed on the Lower Mississippi from Cairo to Baton Rouge [TYLER and FRIEDKIN, 1945, p. 17].

In the foregoing it has been shown that a certain bed load is required to initiate and maintain a meandering process. On the other hand, a superfluous silt content may prevent meandering, as for very large values of β the denominator in (11) becomes zero or imaginary. This latter inference accounts for the occurrence of so-called braided or overloaded rivers, which also have been tested in the Vicksburg laboratory [TYLER and FIREDKIN, 1945, p. 16].

The variation with time of the quantity B_t implies that the meander length increases with time up to a certain limit. This is also in principal agreement with the Vicksburg experiments [TYLER and FRIEDKIN, 1945, plate 25].

Whereas (7) indicates that the initial oscillation attack on a straight stream is clearly related to the width of the river, the derivation of (8) would bear out that in the later serpentine stages there is only a general tendency for a big river to develop big bends. This latter finding, in conjunction with the sensitiveness of the denominator in the formulas to even small variations in its constituents, explains the futility of approaching the meander problem from a purely geographical angle and the failure of all attempts to correlate the various basic factors in meandering by statistical methods only.

The appearance of meander loops with backward movement cannot be derived from the given formulas. Nor could such loops be reproduced in the Vicksburg experiments. It would seem plausible, therefore, to ascribe the formation of loops in nature to inhomogeneities in the stream bed, or like causes [TYLER and FRIEDKIN, 1945, p. 16], and to characterize the loops as a deformity rather than as an integral part of a pattern [MATTHES, 1941]. It is felt, however, that great caution should be exercised in applying the above formulas to such special features of the later meander stages; as previously indicated, we have here to deal with various new factors, such as the centrifugal force in the bends and a pronounced current impingement, which may not be prevalent as decisive factors in the initial serpentine stage.

Eq. (7) in conjunction with (10) shows that the meander length increases with increasing discharge, although generally not in direct proportion. It may be mentioned that the Vicksburg experiments [TYLER and FRIEDKIN, 1945, p. 8] show a rectilinear relation between L and Q, at least within certain intervals. This minor inadequacy may be due to the approximations of the theory.

In this connection it may also be mentioned that our formulas do not account for variations in the boundary conditions at the entrance section. However, the Vicksburg experiments show [TYLER and FRIEDKIN, 1945, p. 10] that the influence of varying boundary conditions is comparatively small, amounting for instance to only about ten per cent of the meander length when doubling the angle of attack from 30° to 60°. Now it is obvious that the entrance conditions must have some effect on the meander pattern. Analogously, the wave-train cannot, of course, persist unchanged against interferences set up by chance disturbances along the stream.

Conclusions--This study aims at a clarification, in principle, of the origin of serpentines and meanders. So far, the development of the further stages in the meandering process does not fall within the scope of the investigation.

The main factors governing the initial formation of serpentines in a straight channel are correlated in a simple formula. Aside from minor discrepancies, this formula agrees at least qualitatively with the general behavior of meandering streams, so far known from observations in nature and in models. It is believed that the theory may be adapted also for quantitative investigations in nature. For this purpose further comparative studies of meandering rivers are desirable, covering the widest possible range of conditions as regards the constituent factors.

References

DAVIS, W. M., The development of river meanders, Geol. Mag., London, v. 10, p. 145, 1903.

de GEER, S., Klarälvens serpentinlopp och flodplan, Sveriges Geol. Undersökning (Swedish Geological Survey), Stockholm, Årsbok 4, no. 8, 1911.

EXNER, F. M., Zur Theorie der Flussmäander, SitzBer. Akad. Wissenschaften, Wien, v. 128, pp. 1453-1473, 1919.

HAMBERG, A., paper read before the Uppsala Naturvetenskapliga Studentsällskaps Geologiska sektion, 26 March, 1908.

HEDIN, S., Scientific results of a journey in Central Asia 1899-1902, v. 1, Stockholm, pp. 195-205, 1904.

JEFFERSON, M. S. W., Limiting width of meander belts, Nat. Geog. Mag., Washington, p. 373, 1902.

LAMB, H., Hydrodynamics, Dover Publ., New York, 1945.
MATTHES, G. H., Basic aspects of stream meanders, Trans. Amer. Geophys. Union, pt. III, pp. 632-636, 1941.
PENCK, A., Morphologie der Erdoberfläche, Verlag Engelhorn, Stuttgart, pp. 259-385, 1894.
RUSSEL, R. J., Physiography of Lower Mississippi Delta, Geol. Bull. 8, Louisiana Geol. Surv., 1936.
SCHOKLITSCH, A., Der Wasserbau, Verlag Springer, Wien, v. 1, pp. 142-145, 1930.
TIFFANY, J. B., and G. A. NELSON, Studies of meandering of model streams, Trans. Amer. Geophys. Union, pp. 644-649, 1939.
TYLER, M. C., and J. F. FRIEDKIN, A laboratory study of the meandering of alluvial rivers, U. S. Waterways Exp. Sta., Vicksburg, 1945.
von BAER, K. E., Ueber ein allgemeines Gesetz in der Gestaltung der Flussbetten, Bull. Acad. Imp. Sci., St. Petersburg, v. 2, pp. 2-49, 218-250, 353-382, 1860.
VUJEVIC, P., Die Theiss, eine potamologische Studie, Geog. Abhandlungen, Verlag Teubner, Leipzig, v. 7, no. 4, 1906.

Note--Comprehensive lists of references are given in the above works of de GEER [1911] and TYLER and FRIEDKIN [1945].

Vattenbyggnadsbyrån,
29 Humlegårdsgatan,
Stockholm, Sweden

(Communicated manuscript received May 16, 1951;
open for formal discussion until May 1, 1952.)

Transactions, American Geophysical Union - Volume 32, Number 6 December 1951

INTERCEPTION OF RAIN AND SNOW BY SECOND-GROWTH PONDEROSA PINE

P. B. Rowe and T. M. Hendrix

Abstract--This paper reports the results of a six-year study to determine interception loss in a fully stocked 65- to 75-year-old second-growth ponderosa pine stand situated near Bass Lake, California. Interception loss was computed as the difference between measured precipitation and the sum of measured throughfall and stemflow.

The average annual precipitation was 47 inches, of which about 84 pct reached the forest floor as throughfall and four per cent as stemflow. Twelve per cent was interception loss. Throughfall, stemflow, and interception loss were directly related to storm size. Regression graphs and equations based upon this relation are given, which permit estimates of interception loss from storm precipitation. An average of four per cent more precipitation reached the forest floor during snow than during rainstorms. However, estimates of annual interception loss are not appreciably improved by use of separate regressions for snowstorms and rainstorms. The interception process is illustrated by rate graphs showing when and how interception loss occurred during a typical storm. Interception loss consisted principally of the water retained by the vegetation during its initial wetting plus that lost by evaporation from the vegetation during storm intervals without precipitation.

Introduction--Part of the precipitation in watersheds supporting forest growth is intercepted by the tree cover. Some of this intercepted precipitation reaches the forest floor as drip from the foliage and branches and as flow down the stems of the trees; the remainder is lost by evaporation from the vegetation. The amount of this interception loss is subject to control by manipulation of the forest cover.

California has about 4.4 million acres of pine cropland [WIESLANDER and JENSEN, 1946]. Of this, 656,000 acres bear large young growth of the same size and age class as that in which the present study was conducted. The importance of second growth is rapidly increasing as more and more old-growth timber is cut. Because water is a valuable resource of these areas, data on interception of rain and snow are needed in solving watershed management problems of this vegetation type.

This paper presents results of a six-year study, started in 1940, to determine effects of a second-growth ponderosa pine stand on the amount and distribution of precipitation reaching the forest floor. The study was one phase of an investigation of water yield and soil erosion in this ponderosa pine stand, the results of which are in process of publication [ROWE and COLMAN, publication pending].

Results of past research in rainfall interception have been summarized by KITTREDGE [1948]. More recently, HAMILTON and ROWE [1949] reported the results of three interception studies in native shrub vegetation of California. Both publications include descriptions of the interception process, and the latter, a rather complete bibliography of interception. However, none of the past studies covered vegetation and climate comparable to those of this study.

Definitions of terms--Interception is the process in which precipitation is caught by vegetation and redistributed as drip, stemflow, or evaporation. Throughfall is that precipitation reaching the forest floor as direct fall through and as drip from the vegetation. Stemflow is that precipitation intercepted by the vegetation which reaches the forest floor as flow down the stems. Interception loss is that precipitation intercepted and lost by evaporation from the vegetation. (Some of the intercepted precipitation may be absorbed directly by the vegetation, but in the present study no attempt was made to distinguish between the absorption and evaporation losses.)

The study area--This study was conducted in the west side ponderosa pine belt of the Sierra Nevada near Bass Lake, California, at an elevation of 3,350 ft. The interception plot, 39.6 × 55 ft long (1/20 acre), was situated on a 36-pct slope facing north by northeast.

The climate of Bass Lake is characterized by wet winters, dry summers, and moderate temperatures. Annual rainfall during the period of record (1904-1946) averaged 42 inches, of which 30 to 40 pct normally occurred as snow. Although winter temperatures above 32°F prevailed,

Fig. 1--Interception plot showing stand characteristics of the second-growth ponderosa pine, Bass Lake, California; the tree collars and collector tanks seen in the photograph were used to collect stemflow, and the standard eight-inch rain gages were used to measure the throughfall

temperatures below freezing were not uncommon during November through March. Owing to the protection afforded the plot by surrounding vegetation and ridges, wind velocities were extremely low.

The timber stand studied (Fig. 1) was a fully stocked 65- to 75-year-old second-growth ponderosa pine containing 560 trees per acre. Trees on the plot ranged from 22 to 111 ft tall, were 3.7 to 17.6 inches in diameter at breast height, and had a total basal area of 2872 sq. in. The average height was 71 ft and the average diameter was 9.8 inches. The estimated density of the crown canopy was about 40 pct.

Method of study--The study was started October 1, 1940 and continued to September 30, 1946. During these six years a total of 214 storms yielded measurable precipitation. Precipitation, throughfall, and stemflow were measured for each storm. Interception loss for each storm was computed as the difference between the measured precipitation and the sum of the measured throughfall and stemflow.

Precipitation was measured by four standard eight-inch rain gages mounted on poles by means of a hoist device [DAVIS, 1939]. These gages were placed at the tree crown surface in depressions of the canopy on each side of the plot. The catch of the pole gages was checked against measurements of precipitation made in three standard eight-inch gages and a 12-inch tipping bucket intensity gage set on the ground in openings near the study area. The intensity gage was also used to measure rainfall rates for the interception study. Each gage was placed to have a vertical clearance of 45° from the tops of surrounding trees, and the funnels were removed from all but the intensity gage during periods of snowfall. Differences in the annual catch of pole and ground gages averaged less than 0.8 pct.

When snow occurred in amounts too great to permit accurate measurement in the rain gages, precipitation was measured at a snow station in a clearing about 250 ft from the plot. The snow station consisted of two canvas-covered catchment areas for measuring daily snowfall, a similar area for measuring cumulative fall, and two 500-sq. in. snow pans. The snow pans were used to measure rain occurring during snow periods and for measuring rates and amounts of snow melt.

Throughfall was measured by 24 standard eight-inch rain gages placed at random on the ground within the interception plot. Six of these gages were equipped with tipping buckets for determining throughfall rates. When throughfall occurred as snow in amounts too great to be measured in the gages, it was calculated from snow samples collected near each throughfall gage and along a snow course consisting of 18 canvas-covered catchment areas. Six 500-sq. in. snow pans similar to those at the open snow station were used to determine amounts of rain occurring during a snow period, and rates and amounts of snow melt. The average throughfall catch of the snow

Table 1--Annual distribution of precipitation to throughfall, stemflow, and interception loss in second-growth ponderosa pine, Bass Lake, California

Year	Character of precipitation	Number of storms	Precipitation	Distribution of precipitation to					
				Throughfall	Stemflow	Interception loss	Throughfall	Stemflow	Interception loss
			inch	inch	inch	inch	pct	pct	pct
1940-41	Rain	36	49.3	41.0	1.9	6.4	83.2	3.9	12.9
	Snow[a]	5	9.2	7.6	0.4	1.2	82.6	4.4	13.0
	All	41	58.5	48.6	2.3	7.6	83.1	3.9	13.0
1941-42	Rain	29	33.4	27.2	1.1	5.1	81.4	3.3	15.3
	Snow	6	16.4	14.4	0.6	1.4	87.8	3.7	8.5
	All	35	49.8	41.6	1.7	6.5	83.5	3.4	13.1
1942-43	Rain	34	33.8	28.1	1.5	4.2	83.1	4.5	12.4
	Snow	6	17.1	14.8	1.0	1.3	86.6	5.8	7.6
	All	40	50.9	42.9	2.5	5.5	84.3	4.9	10.8
1943-44	Rain	30	17.9	14.6	0.5	2.8	81.5	2.8	15.7
	Snow	13	19.8	17.1	0.4	2.3	86.4	2.0	11.6
	All	43	37.7	31.7	0.9	5.1	84.1	2.4	13.5
1944-45	Rain	22	26.2	22.0	1.0	3.2	84.0	3.8	12.2
	Snow	11	24.1	21.1	0.6	2.4	87.5	2.5	10.0
	All	33	50.3	43.1	1.6	5.6	85.7	3.2	11.1
1945-46	Rain	16	24.9	20.9	0.7	3.3	83.9	2.8	13.3
	Snow	6	11.9	10.5	0.1	1.3	88.2	0.9	10.9
	All	22	36.8	31.4	0.8	4.6	85.3	2.2	12.5
Annual averages	Rain	28	30.9	25.6	1.1	4.2	82.8	3.6	13.6
	Snow	8	16.4	14.3	0.5	1.6	87.2	3.0	9.8
	All	36	47.3	39.9	1.6	5.8	84.3	3.4	12.3

[a]Storms in which 50 pct or more of the precipitation fell as snow.

pans was practically the same as the average catch of the 24 standard eight-inch gages.

Stemflow was measured for all trees on the interception plot. It was caught by a watertight trough-like collar fitted around each stem at 4.5 ft from the ground, from which it was diverted to collector tanks. Fifteen of the 29 stemflow collector tanks were equipped with tipping buckets for recording stemflow rates.

Annual interception--During the period of this study, annual precipitation ranged from 36.8 to 58.5 inches, averaging 47.3 inches, or about five inches more than the long-time average for the vicinity. Throughfall averaged 39.9 inches, or 84.3 pct of the annual precipitation; stemflow averaged 1.6 inches, or 3.4 pct; and interception loss averaged 5.8 inches, or 12.3 pct.

Amounts of annual throughfall, stemflow, and interception loss increased with increases in precipitation (Table 1). The percentage of annual precipitation going to these components of the interception process, on the other hand, varied only slightly from year to year. The variations were not related to amounts of annual precipitation. Instead, they reflected the influences of other factors, such as the number and size of storms and the character and distribution of the precipitation through the rainy season.

Relation of interception to storm size--Throughfall, stemflow, and interception loss were directly related to storm size. For storms of more than 0.5 inch, each of these components bore a straight-line relation to storm precipitation (Fig. 2). For smaller storms, precipitation was insufficient to wet the vegetation completely, and these relations became curvilinear. The close grouping of the observed data about their respective regression lines indicates the importance of storm size in determining interception loss.

Interception loss can be read directly from the regression graph if storm precipitation is known, or it can be computed for storms of more than 0.5 inch precipitation by use of the regres-

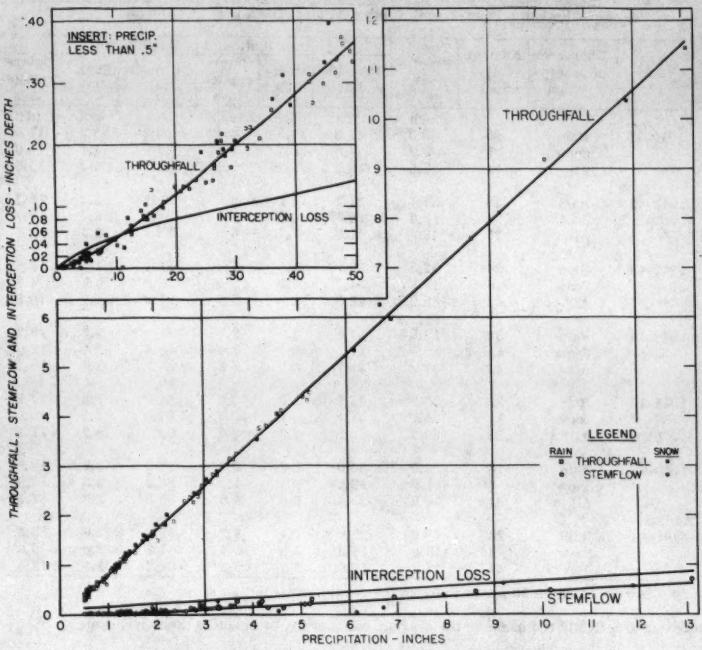


Fig. 2--Relation of throughfall, stemflow, and interception loss to storm size in second-growth ponderosa pine, Bass Lake, California

sion equation, IL = 0.06P + 0.11. In this equation IL is the interception loss in inches, P is the storm precipitation in inches, 0.06 is the proportion of precipitation lost by evaporation from vegetation throughout the course of a storm, and 0.11 is the amount of precipitation (inches) retained in wetting the vegetation at the beginning of the storm. The standard error of estimate is 0.086.

Although precipitation exceeded 0.5 inch in only about half the storms included in this study, these storms contributed about 94 pct of the total precipitation. Because of the water retained in initial wetting of the vegetation, the proportion of precipitation lost by interception decreased rapidly with increase in storm size. Interception losses ranged from less than seven per cent of the precipitation in the largest storms to over 80 per cent in small storms.

Effects of snow on interception--Throughfall was generally greater, and stemflow and interception loss were usually less in snowstorms than in rainstorms (Table 1 and Fig. 2). When all storms included in the study were considered, interception loss averaged 9.8 pct of the precipitation in snowstorms and 13.6 pct of the precipitation in rainstorms. Thus, an average of 3.8 pct more of the precipitation reached the forest floor during snowstorms than during rainstorms.

Part of the difference in interception loss between snowstorms and rainstorms was due to differences in storm size. Precipitation for rainstorms averaged about 1.1 inches per storm, and for snow storms about 2.1 inches per storm. The 47 snowstorms recorded during the study are matched with 47 rainstorms of comparable size and season of occurrence in Table 2. The

Table 2--Disposition of rain and snow

Item	Snowstorms		Rainstorms	
	inch	pct	inch	pct
Precipitation	98.4	100.0	99.7	100.0
Throughfall	85.8	87.2	83.6	83.9
Stemflow	3.0	3.0	3.8	3.8
Interception loss	9.6	9.8	12.3	12.3

difference in interception loss shown in this tabulation is less than that found when all rainstorms are included, yet it amounts to 2.5 pct of the total precipitation.

The principal reason for the difference in interception loss between snowstorms and rainstorms can be found by examination of the following regression equations.

Snowstorms $IL = 0.06P + 0.09 \pm 0.101$
Rainstorms $IL = 0.06P + 0.12 \pm 0.079$

These equations are for storms of over 0.5-inch precipitation, and are of the same type as the interception loss equation for combined rainstorms and snowstorms. The evaporation coefficients are the same in each equation, indicating that the rate of evaporation loss from the vegetation was about the same during snowstorms as during rainstorms. The wetting coefficient, the second constant of each equation, is, however, slightly less for snow than for rain. This indicates that the smaller interception loss for snow was due principally to less water being retained in wetting the vegetation than when precipitation occurred as rain.

The regression equations show that the differences between interception losses in comparable snowstorms and rainstorms are small. Furthermore, the standard errors of the equations indicate that little significance can be attached to these small differences. Therefore, estimates of annual interception loss are not appreciably improved by the use of the separate regressions for rainstorms and snowstorms.

Relation of throughfall and stemflow to stand characteristics--Throughfall and stemflow, while directly related to amount and character of storm precipitation, varied greatly within the stand. Annual throughfall, as measured by the catch of individual gages, ranged from 58 to 120 pct of annual precipitation. The higher catches were apparently due to concentrations of throughfall as drip from the vegetation. Although there were consistent differences between gage catches, there was no apparent relation between gage catch and the density of cover immediately above the gage or the distance of the gage from individual trees. Throughfall at any spot, therefore, appeared to depend more upon canopy characteristics of the surrounding stand than upon the crown characteristics of any single tree.

In general, large trees produced more stemflow than small trees. Individuals among the smaller trees on the plot (trees ranging from four to ten inches in diameter) contributed between 0.5 and 3.5 pct of the total stemflow, while individuals among the larger trees contributed between 1.0 and 12.0 pct. However, the relation between stemflow and tree size was not consistent and could not be depended upon in estimating stemflow of individual trees.

How interception loss occurs--The interception process has been admirably described by HORTON [1919]. More recently his concepts have been corroborated and shown graphically for chaparral species by HAMILTON and ROWE [1949]. Interception loss in second-growth ponderosa pine occurs by the same processes as in the chaparral.

Data are shown in Figure 3 illustrating the interception process during a typical storm in the second-growth ponderosa pine at Bass Lake. The curves showing the accumulated amounts of rainfall, throughfall, and stemflow throughout the storm are based on measurements. The interception storage curve shows successive differences between rainfall and the sum of throughfall and stemflow. Each point on this curve represents the amount of rainfall in storage on the vegetation plus the amount lost by evaporation during the preceding portion of the storm. The comparison of this curve with the rainfall, throughfall, and stemflow curves indicates when and how interception loss occurs.

At the beginning of storms, interception storage increases with the amount of storm precipitation until the storage capacity of the vegetation is reached. When rainfall continues after the vegetation becomes completely wetted, the combined rates of throughfall plus stemflow become nearly equal to the precipitation rate. Once storage capacity has been reached, interception storage increases only slightly with time, but undergoes minor fluctuations when the vegetation is disturbed by wind and beating rain. Thus, evaporation losses during periods of continuing precipitation constitute a relatively small portion of the total interception loss.

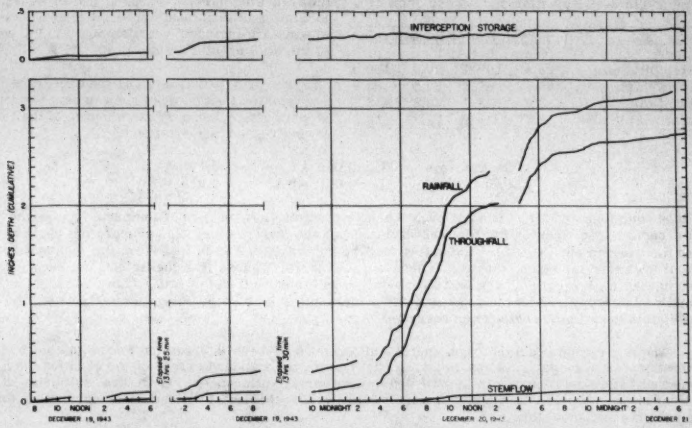

INTERCEPTION STORAGE
RAINFALL
THROUGHFALL
STEMFLOW
INCHES DEPTH (CUMULATIVE)
Elapsed time 15 hrs 25 min
Elapsed time 15 hrs 30 min
8 10 NOON 2 4 6
DECEMBER 19, 1943
2 4 6 8
DECEMBER 19, 1943
10 MONIGHT 2 4 6 8 10 NOON 2 4 6 8 10 MONIGHT 2 4 6
DECEMBER 20, 1943
DECEMBER 21

Fig. 3--Cumulative rainfall, throughfall, stemflow, and interception storage for a typical storm in second-growth ponderosa pine, Bass Lake, California

Storms generally consist of alternating periods with and without precipitation. Some intercepted water is usually lost by evaporation from vegetation during the rainless periods; the amount is dependent upon the length of period and prevailing atmospheric conditions. Portions of the subsequent precipitation are used in replenishing this loss, and interception storage is correspondingly increased. Interception loss, therefore, is principally the water retained by the vegetation during its initial wetting at the beginning of storms, plus the water lost by evaporation from the vegetation during storm intervals without precipitation.

Acknowledgment--The authors are indebted to the many members of the California Forest and Range Experiment Station staff who through their suggestions or help have contributed to this study. T. W. Daniel's assistance in the development and installation of the experimental equipment and John W. Schmidt's help in the maintenance and operation of the experimental installations during part of the study are particularly appreciated.

References

DAVIS, WENDELL C., Measurement of precipitation above forest canopies, J. Forestry, v. 37, no. 4, pp. 324-329, 1939.

HAMILTON, E. L., and P. B. ROWE, Rainfall interception by chaparral in California, Calif. Forest and Range Exp. Sta., 43 pp., 1949.

HORTON, R. E., Rainfall interception, Mon. Weather Rev., v. 47, pp. 603-623, 1919.

KITTREDGE, JOSEPH, Forest influences, McGraw-Hill, 394 pp., 1948.

ROWE, P. B., and E. A. COLMAN, Disposition of rainfall in two mountainous areas of California, U. S. Dept. Agri., publication pending.

WIESLANDER, A. E., and HERBERT A. JENSEN, Forest areas, timber volumes, and vegetation types in California, Calif. Forest and Range Exp. Sta., Forest Surv. Release No. 4, 66 pp., 1946.

California Forest and Range Experiment Station,
Berkeley, California

(Manuscript received March 30, 1951; presented at the Twenty-Sixth Meeting, Fresno, California, February 9, 1951; open for formal discussion until May 1, 1952.)

Transactions, American Geophysical Union Volume 32, Number 6 December 1951

TURBULENCE FLUME TO MEASURE BED LOAD

Maurice L. Albertson

Abstract--In order to develop a method of measuring bed load in an alluvial stream, a turbulence flume was designed and tested in the Hydraulics Laboratory of Colorado Agricultural and Mechanical College. This flume has a number of advantages over other methods of measuring bed load because it operates continuously so that the stream is constantly in equilibrium. A system of baffles was used to create sufficient turbulence to force the bed load into suspension so that the entire load of the stream could be measured by means of suspended load samplers. The extreme roughness of the baffles eliminated the effect of the Reynolds number in the immediate vicinity of the turbulence flume, thereby making it possible to utilize model studies for determining in advance the optimum size and arrangement of baffle plates. The structure has been in use for three years and has operated satisfactorily as predicted.

Prior to the construction of a diversion works on the Middle Loup River for an irrigation project in the sand-hill region of north-central Nebraska, joint action was taken by the United States Geological Survey and the United States Bureau of Reclamation to determine as accurately as possible the bed load and suspended load of sediment in the Middle Loup River at Dunning, Nebraska. Through P. C. Benedict, regional engineer of the Quality of Water Branch of the Geological Survey in the Missouri River Basin, a contract was negotiated with the Research Foundation of Colorado Agricultural and Mechanical College to design and test by laboratory models a structure which would make possible the measurement of the total sediment load in the stream. The highway bridge at Dunning was chosen as the site for the structure. The field installation has been described by SERR [1951].

Although the size of the watershed upstream from the proposed structure is approximately 1850 sq mi as determined from topographic maps, the area actually contributing to surface runoff is estimated at only 93 sq mi. The entire watershed is in sand-hill country so that most of the stream flow comes from ground water. As a result, the maximum instantaneous runoff on record is only 821 cfs whereas the minimum is 220 cfs. Visual observation indicates that most of the sediment load and the bed material originates from caving of the banks of the stream. The mean size of the bed material was determined to be 0.35 mm. Specifications for the design of the structure were that a measurement of 2000 ppm of total sediment load be made possible.

Although standard equipment is now available for measuring the suspended load in a relatively simple manner [INTERAGENCY, 1940], measurement of the bed load in a stream has not been possible except by means of rather elaborate structures for trapping the sediment moving along the stream bed. In order to simplify the structure, have a continuously operating process, and permit exclusive use of the standard suspended-load sampling equipment, a design which would force the entire sediment load into suspension was selected. For the stream to carry all of the load in suspension, its carrying capacity must be increased by increasing the turbulent-energy content. The additional energy may be supplied either by utilizing the energy of the stream itself or from some external source such as an electric motor or a gasoline engine. Because of the requirement of a continuous process so that equilibrium conditions would prevail at all times, however, the external-energy possibilities were dropped from consideration as being uneconomical.

In order to create additional turbulence near the bottom of the stream where it is needed to pick up the bed load, it was decided to use roughnesses placed on the stream bed. The first attempt was to use continuous baffles placed across the flow with a longitudinal spacing such that the greatest loss in total energy would be obtained, this condition logically being the one which would create the greatest turbulence. POWELL [1946] and JOHNSON [1944] found that the longitudinal spacing which created the greatest resistance was approximately 12 times the height of the baffle. However, when continuous baffles were used in the model tests, each baffle was slowly but surely covered by the sediment as it moved downstream. To remedy this situation, baffle plates with open spaces between them were installed to permit movement of that part of the bed load which had not yet been forced into suspension. Experimentation proved the effectiveness of this design and each additional row of baffles added to the turbulence until the entire bed load was in suspension.

Table 1--Ratio W/V of the mean fall velocity of the sediment to the velocity of flow in the river

Discharge	Prototype	Model
cfs		
200	0.098	0.16
400	0.072	0.12
800	0.051	0.084
1200	0.042	0.070

Each laboratory test was made with the Froude number the same for the model as for the prototype. To make the similitude as nearly complete as possible, an attempt also was made to keep the velocity ratio W/V the same for the model and prototype for any particular flow [KRUMBEIN, 1942; ROUSE, 1939; DODDIAH, 1949]. In this ratio, W is the mean fall velocity of the sediment and V is the velocity of flow in the stream. Maintaining similarity with regard to the velocity ratio, however, was difficult because of the small size of sediment required for the model. Table 1 shows the velocity ratios for the model and prototype. As may be seen in the table, the sand used in the model was always larger than necessary for similarity. This deviation, however, is in the direction of safety because if it is possible to force in suspension sand of a given fall velocity it will certainly be possible to force in suspension the same concentration of a smaller sand having a lower fall velocity. Reynolds number was not considered to enter the problem because of the turbulence in the flume which no doubt destroyed the laminar sublayer, thereby making the viscous forces unimportant compared with the forces of inertia.

Following the preliminary tests which were made with a model-prototype scale ratio of 1:8, the final investigations were made on a sectional model having a scale ratio of 1:4. These experiments revealed that nine rows of baffle plates placed six feet on centers across the flow and two feet apart in the direction of flow were adequate to force 2000 ppm into suspension provided the baffles were two feet long and one foot high. When the baffles were only six inches high, however, the sand dunes moved downstream to cover the baffles almost completely.

When the baffles were one foot high, a sand dune would almost cover an upstream baffle as the crest of the dune reached it, but the baffle would be completely uncovered when the trough of the dune was passing. By the time the dune reached the downstream end of the structure, however, the sand passed the measuring sill entirely in suspension.

As a result of the laboratory tests, the final recommendations were to have the baffle plates a minimum of one foot in height and placed so that each baffle was centered downstream from the four-foot space between the baffles in the row immediately upstream [see SERR, 1951]. In order to help equalize the influence of the baffle plates, it was recommended that a continuous six-inch baffle be placed two feet downstream from the last row of baffles and two feet upstream from a measuring sill. The measuring sill was six inches high by 18 inches wide so that the flow would be moving nearly parallel to the sill as it entered the sampler. It was planned that the sampler would be lowered past the downstream edge of the sill when measurements were being taken.

The structure has been built and operated by the U. S. Geological Survey since the summer of 1949 [SERR, 1951] and inspections made by the writer of the flow and sediment pattern in the prototype showed it to be working satisfactorily. With one-foot baffles, all sediment small enough to be measured by the sampler was forced into suspension. Furthermore, the patterns and the movement of the sand dunes upstream from and through the structure were found to be almost identical quantitatively with what was found by the model studies.

As far as the writer knows, this is the first bed-load measurement structure that has been built which operates continuously and permits the entire sediment load of the stream to be measured with a suspended-load sampler. The model-prototype comparison demonstrates rather conclusively the possibility of making quantitative measurements of the movement of sediment in a model provided the viscous effects, as reflected in the laminar sub-layer, are eliminated in both the model and prototype.

The design of the structure and the model tests were made in the Hydraulics Laboratory at the college and were under the direction of the writer [ALBERTSON, 1948].

References

ALBERTSON, M. L., Design of the Loup River bed-load measurement structure, final rep., Colo. A. and M. College, July 1948 (unpublished).

DODDIAH, DODDIAH, Comparison of scour caused by hollow and solid jets of water, Thesis M.S. in Irrig. Eng., Colo. A. and M. College, December 1949 (unpublished).

INTERAGENCY, Rep. No. 1, Field practice and equipment used in sampling suspended sediment; measurement and analysis of sediment loads in streams, St. Paul (Minnesota) Engineer Dist. Office, August 1940.

JOHNSON, J. W., Rectangular artificial roughness in open channels, Trans. Amer. Geophys. Union, pt. 6, pp. 906-914, 1944.
KRUMBEIN, W. C., Settling velocities and flume behavior of non-spherical particles, Trans. Amer. Geophys. Union, pt. 2, pp. 621-632, 1942.
POWELL, R. W., Flow in a channel of definite roughness, Trans. Amer. Soc. Civil Eng., v. 111, pp. 531-566, 1946.
ROUSE, HUNTER, Criteria for similarity in transportation of sediment, Proc. Iowa Hydraulics Conference, Univ. of Iowa Studies, Eng. Bull. 20, 1939.
SERR, E. F., Measurement of bed-load sediment, Trans. Amer. Geophys. Union, v. 32, pp. 123-126, 1951.

Department of Civil Engineering,
Colorado Agricultural and Mechanical College,
Fort Collins, Colorado

(Manuscript received April 30, 1951; presented at the Thirty-Second Annual Meeting, Washington, D. C., May 1, 1951; open for formal discussion until May 1, 1952.)

THE USE OF MODIFIED ORTHOGRAPHIC PROJECTIONS IN STRUCTURAL GEOLOGY

V. G. Gabriel and Milton A. Sobie

Abstract--Simplified diagrams based on the theory of orthographic projections are derived for rapid solution of various field problems commonly encountered in structural geology. A few examples for the solution of field problems with the use of these diagrams are given.

Introduction--The application of stereographic projections to the solution of various problems usually encountered in structural geology is quite widespread at the present time. BUCHER [1944], BECKWITH [1947], FISHER [1941], MACELWANE [1912], and others have made valuable contributions to the application of stereographic projections in geology and seismology. However, in spite of the wide use of stereographic methods, their usefulness is somewhat limited because of the difficulties inherent in visualizing the various structures of the Earth in terms of stereographic projections. On the other hand, the structures expressed through the application of orthographic methods are easier to visualize; moreover, they are more amenable to simpler mathematical interpretations than those derived with the use of stereography.

The problem--We can assume, at least during the first steps, that the surface of the Earth is a horizontal plane and that our Earth block is a hemisphere whose radius R is equal to ten units (see Fig. 1), where the diameter AA is oriented in the true north-south direction and the diameter BB along an east-west line. By passing two vertical planes KKK_1K_1 and TTT_1T_1, which can serve as the two side views, any structure under consideration can be orthogonally mapped on three mutually perpendicular surfaces AABB (plan view), TTT_1T_1 (side view), and KKK_1K_1 (second side view).

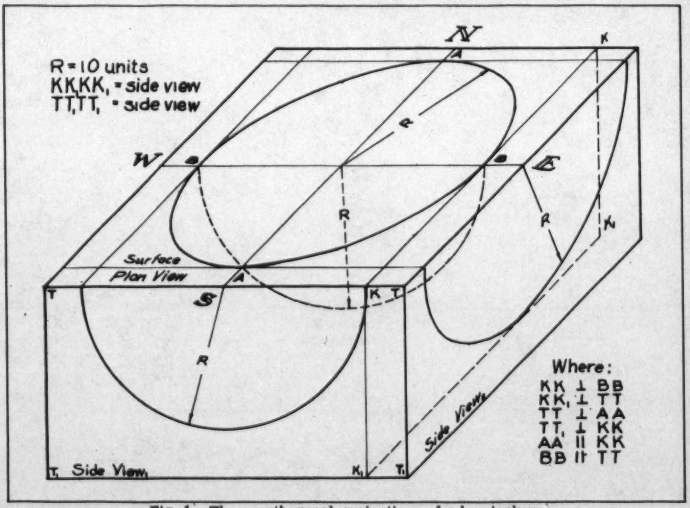


Fig. 1--Three orthogonal projections of a hemisphere

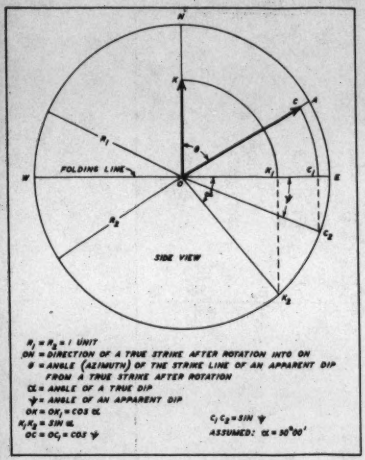


Fig. 2--Graphical illustration of Eq. (1)

Graphical solutions in the field can be greatly expedited and simplified by employing a radius R of the hemisphere equal to ten units (for example, ten inches) and with the azimuth lines drawn at two-degree intervals on a semicircle of a diagram. This semicircle represents a plan view of the surface of the Earth.

Analysis--According to a well-known formula

$$\tan\psi = \tan\alpha \cos\theta \quad \ldots\ldots\ldots (1)$$

where (see Fig. 2) ψ = angle of an apparent dip, α = angle of a true dip, and θ = angle of the strike line of an apparent dip from a true strike.

Equation (1) can be expressed as

$$\sin\psi/\cos\psi = \tan\alpha \cos\theta. \ldots\ldots (2)$$

or from (2) we have

$$\cos\psi = \sin\psi/\tan\alpha \cos\theta. \ldots\ldots (3)$$

By using (1) or (3) the cosines of apparent angles of dip can be computed (see Table 1) and plotted along their respective strike lines on a diagram containing all three projections for any angle of true dip.

A multiplication factor equal to ten has been introduced in order that any plane passing

Table 1--Cosines of apparent angle of dip

TRUE DIP		APPARENT AZIMUTH										
		0°	5°	10°	20°	30°	40°	50°	60°	70°	80°	85°
5°	Apparent ψ [*]	5°00'	4°59	4°55	4°42'	4°20'	3°50'	3°13'	2°30'	1°43'	0°52'	0°26
	Cosine ψ [**]	0.9962	0.9963	0.9963	0.9966	0.9971	0.9978	0.9984	0.9990	0.9995	0.9999	0.9999
10°	Apparent ψ	10°00	9°58'	9°51'	9°25'	8°41'	7°41'	6°28'	5°03'	3°27'	1°43'	0°53'
	Cosine ψ	0.9848	0.9849	0.9852	0.9866	0.9885	0.9910	0.9936	0.9961	0.9982	0.9995	0.9998
20°	Apparent ψ	20°00'	19° 56'	19°43'	18°53'	17°30'	15° 36'	13° 10'	10° 19	7° 06'	3° 37'	1° 49'
	Cosine ψ	0.9397	0.9401	0.9414	0.9462	0.9537	0.9632	0.9737	0.9836	0.9923	0.9980	0.9995
30°	Apparent ψ	30° 00'	29° 55'	29° 37'	28° 29'	26° 34'	23° 52'	20° 22'	16° 06'	11° 10'	5° 43'	2° 55'
	Cosine ψ	0.8660	0.8646	0.8693	0.8789	0.8944	0.9145	0.9374	0.9607	0.9810	0.9950	0.9987
40°	Apparent ψ	40° 00'	39° 54'	39° 24'	38° 16'	36° 00'	32°46'	28° 20'	22° 48'	16° 01'	8° 18'	4° 11'
	Cosine ψ	0.7660	0.7672	0.7709	0.7852	0.8089	0.8412	0.8802	0.9221	0.9611	0.9895	0.9978
50°	Apparent ψ	50° 00	49°54'	49° 34'	48° 16'	45° 58'	42° 24'	37° 29'	30°48'	22° 11'	11°42'	5° 56'
	Cosine ψ	0.6428	0.6441	0.6484	0.6650	0.6958	0.7385	0.7936	0.8580	0.9260	0.9792	0.9946
60°	Apparent ψ	60°00	59°54'	59° 37'	59°22	56°18	53°00'	48° 04'	40° 54'	30° 58'	16°44'	8° 35'
	Cosine ψ	0.5000	0.5016	0.5067	0.5236	0.5547	0.6019	0.6682	0.7559	0.8604	0.9578	0.9888
70°	Apparent ψ	70°00	69° 53'	69° 43'	69°49	67°12	64°36'	60° 29'	53° 54'	43° 13'	25° 30'	15° 28'
	Cosine ψ	0.3420	0.3453	0.3467	0.3612	0.3875	0.4282	0.4928	0.5886	0.7288	0.9026	0.9725
80°	Apparent ψ	80° 00'	79° 58'	79° 51'	79° 22'	78° 29'	77°02'	74° 59'	70° 34	62° 44'	44°33	24° 20'
	Cosine ψ	0.1736	0.1743	0.1763	0.1844	0.1986	0.2243	0.2665	0.3323	0.4583	0.7126	0.8964
85°	Apparent ψ	85°00'	84° 58'	84° 53'	84° 41'	84° 14'	83° 29'	82° 15	80° 06	75° 39	65° 15'	44° 34
	Cosine ψ	0.0872	0.0876	0.0886	0.0927	0.1005	0.1134	0.1349	0.1724	0.2478	0.4501	0.7083

* ψ angles correct to the nearest minute.

** Cosines of apparent angles are taken to the fourth decimal place.

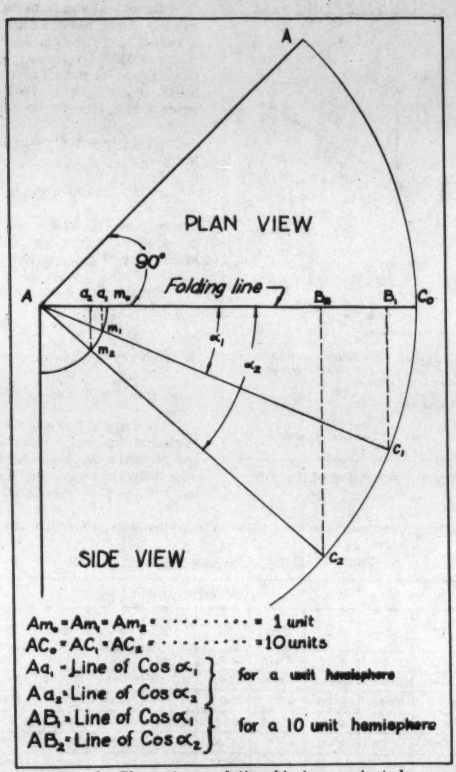


Fig. 3--Elementary relationship in a projected hemisphere

through the line AA (see Fig. 1 and 3) of the plan view and dipping at various angles, such as α_1, α_2, α_3, ... α_n, will cut a unit hemisphere $Am_0m_1m_2$, and a ten-unit hemisphere $AC_0C_1C_2$, both located in a side-view plan TTT_1T_1, at the points m_1, m_2 ...., and C_1, C_2 ...., respectively.

By assuming that $Am_1 = Am_2 = \ldots = Am = 1$ for a unit sphere and $AC_1 = AC_2 = \ldots = ACN = 10$ for R = 10 units, we obtain for a unit hemisphere

$$\left.\begin{aligned} \text{Cos } \alpha_1 &= Aa_1/Am_1 = \text{line of cos } \alpha_1/\text{radius} = Aa_1/1 = Aa_1 \\ \text{Cos } \alpha_2 &= Aa_2/Am_2 = \text{line of cos } \alpha_2/\text{radius} = Aa_2/1 = Aa_2 \\ \text{Cos } \alpha_n &= Aa_n/Am_n = Aa_n/1 = Aa_n \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots (4)$$

Similarly for a hemisphere whose radius R = 10 units, we have

$$\text{Cos } \alpha_1 = AB_1/AC_1 = AB_1/10 = 10(Aa_1)/10 = Aa_1$$

where $10(Aa_1) = AB_1$ = line of cos α_1

$$\text{Cos } \alpha_2 = AB_2/AC_2 = 10(Aa_2)/10 = Aa_2$$

where $10(Aa_2) = AB_2$ = line of cos α_2

. . . . . (5)

. . . . . .

$$\text{Cos } \alpha_n = \ldots\ldots = Aa_n$$

where $10(Aa_n) = Aa_n$ = line of cos α_n

Fig. 4 comprises all three projections, where the semicircle OWAE is a plan view, the semicircle OETW is a side view, and the semicircle OAET is a second side view. The lines 0-5°, 0-10°, 0-20° . . . . are the apparent strikes of the lines whose true strikes are located along the

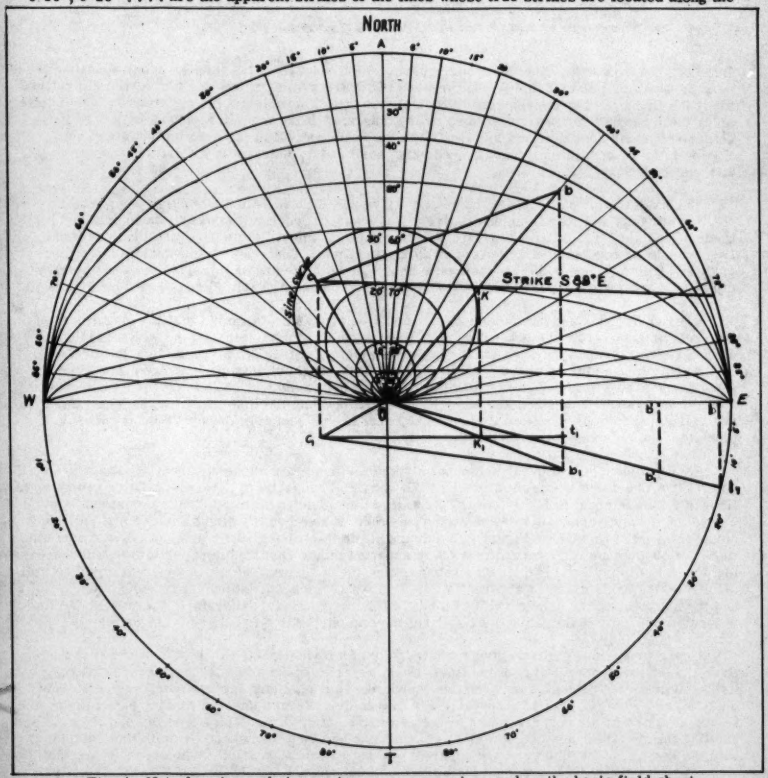


Fig. 4--Net of cosine and sine vector curves superimposed on the basic field sheet of three orthogonal projections

Table 2--Sines of apparent angle of dip

TRUE DIP		APPARENT AZIMUTH										
		0°	5°	10°	20°	30°	40°	50°	60°	70°	80°	85°
5°	Apparent ψ *	5°00'	4°59'	4°55'	4°42'	4°20'	3°50'	3°15'	2°30'	1°43'	0°52'	0°26'
	Sine ψ **	0.0872	0.0868	0.0859	0.0820	0.0754	0.0669	0.0562	0.0437	0.0299	0.0152	0.0076
10°	Apparent ψ	10°00'	9°58'	9°51'	9°25'	8°41'	7°41'	6°28'	5°03'	3°27'	1°45'	0°53'
	Sine ψ	0.1736	0.1730	0.1710	0.1635	0.1509	0.1337	0.1126	0.0885	0.0602	0.0307	0.0154
20°	Apparent ψ	20°00'	19°56'	19°43	18°53'	17°30'	15°35'	13°10'	10°10'	7°06'	3°37'	1°49'
	Sine ψ	0.3420	0.3409	0.3375	0.3238	0.3006	0.2688	0.2278	0.1790	0.1236	0.0631	0.0317
30°	Apparent ψ	30°00	29°53'	29°37'	28°20'	26°34'	23°52'	20°22'	16°06'	11°10'	5°43'	2°53
	Sine ψ	0.5000	0.4986	0.4943	0.4769	0.4472	0.4045	0.3480	0.2774	0.1937	0.0996	0.0503

* ψ angles correct to the nearest minute.

** Sines of apparent angles of dip are computed to the fourth decimal place.

line OA (that is, north). The continuous curves which start from the line OA and gradually converge toward the points E and W are the lines of apparent dips for any angle of a true dip marked along the line OA. For convenience in the solution of field problems, the apparent dips are plotted along their respective apparent strikes on the diagram. If the true or apparent strikes of the structures under consideration are located in the southern half of the diagram not given here, Figure 4 can be conveniently used by replacing north, east, and west of the figure by south, west, and east respectively.

The examination of Figure 4 shows that for relatively low true dips the use of cosine lines will lead to graphical solutions of relatively low accuracy, not comparable to those obtained for medium and high true dips. Therefore, for true dips less than, let us say, 30°, the use of sine lines should be recommended in place of the cosine lines. The sines of apparent dips for the angles of true dips under 30° can be easily computed with the use of (1). The sines of apparent dips for true dips of 30°, 20°, 10°, and 5° have been computed (Table 2) and plotted on Figure 4.

In using the sine and cosine curves, it should be always kept in mind that the magnitudes of the vectors drawn from the central point of the diagram to their intersections with a particular curve give the apparent cosines (or the apparent sines) of a true dip marked along the line AA. The direction of a sine or cosine vector represents the angle of an apparent strike line from the line of true strike assumed to be along the line OA. It is worthy of notice that for a plane whose true dip is equal to α degrees and whose true strike is along the line OA of the diagram (if not, it can be rotated into OA position) its cosine and sine are projected in their true magnitudes on a plan view and side view respectively.

First problem--Find the true dip and strike of a formation whose apparent strikes are N 20° E and N 50° E and whose apparent dips are 45°E and 32°E respectively. Solution: Draw two straight lines at an angle equal to 50° minus 20°, that is, at an angle equal to 30° from a common point on a sheet of tracing paper. Rotate the strike line N 20° E and then the strike line N 50° E until they coincide with the line OA of Figure 4, and mark off on the tracing paper along the drawn azimuth lines the cosines corresponding to the given apparent dips. Then rotate paper toward the decreasing apparent dip until the two vectors representing the cosines of the given apparent dips are well located on the same curve of apparent dips. The two vectors will indicate a true dip equal to 50° and the apparent strike equal to N 30° E and N 60° E respectively. Therefore, the true strike line is located 30° west of the N 20° E strike line; the true strike line is N 10° W, approximately.

Second problem--The true strike and true dip of a formation are N 30° W and 70° E respectively. Find the apparent dips of the lines whose apparent strikes are N 20° E and N 40° E respectively. Solution: The angles between the true strike line and their apparent strikes are 50° (30° plus 20°) and 70° (30° plus 40°) respectively. By scaling off on a sheet of tracing paper the cosine vector of apparent dip corresponding to the respective azimuth lines on a true dip of 70° curve and rotating the tracing paper until the first azimuth line and then the second azimuth line coincide with the line OA of the diagram, the apparent dip angles can be read off. The apparent angle of dip equals 61° for the N 20° E apparent strike line and 43° approximately for the N 40° E strike line.

Three-point problem [after NEVIN, 1949]--Drill hole b is 1600 ft N 40° E of drill hole a, and

drill hole c is 800 ft N 20° W of a. The three drill holes are located on a plane, and the same horizon or marker bed is encountered at the following depths: a, 1254 ft; 1654 ft; and c, 1454 ft. Determine the strike and dip. Let us assume that OA, 10-unit radius, equals 2000 ft. Solution: Assume that the marker bed under a is located at the center point O of the plan view of Figure 4. Similarly the points b and c represent the projections of the marker bed under the drill holes b and c on the plan view spotted in accordance with their azimuths and distances (Fig. 4). On the side view the marker bed points will be located at the points a, b_1, c_1, whose depths will equal 0 ft, (1654 - 1254) ft, and (1454 - 1254) ft respectively or 0 ft, 400 ft, and 200 ft respectively.

On the side view, line c_1b_1 represents the projection of a line cb; on the side view, line Ob_1 represents the projection of a line Ob; on the side view, line Oc_1 represents the projection of a line Oc.

A line c_1t_1 drawn parallel to the folding line WOE is the side-view projection of the strike line of the marker bed at 200 ft below the surface level. The line c_1t_1 is cutting the line Ob_1 at point K_1 whose plan-view projection is point K located on the line Ob. Therefore, the true strike line is line cK whose strike is equal to S 99° E approximately.

To find the true dip of the plane under consideration let us rotate the OKb until it coincides with line OE. By rotation, b goes into b^1 whose projection on the side view is point b^1_1 located 400 ft below the folding line OE. By drawing a straight line Ob_1 1_1 and by projecting point 1_1 on the plan view, the apparent angle of dip and the sine of the angle of dip can be scaled off and measured with the aid of a sine curve or a protractor. The angle $1O1_1$ equals approximately 14°, but this angle is the apparent dip of the line Ob. However, the angle between the line Ob and the line of true strike is 90° - 40° + 2° = 52°. The angle between the line Ob and the line of true dip is 90° - 52° = 38°. Therefore, by scaling off a line of sine 11_1 which may also be regarded as a sine curve vector along the 38° azimuth line, we see that this vector corresponds to a true dip equal approximately to 17° northeast.

Fourth problem [after Billings and Ingerson]--A vein that strikes N 40° E and dips 40° northwest intersects a vein that strikes N 30° W and dips 55° northeast. What is the attitude of the intersection (see Fig. 5)? Solution: Draw the lines ON_1 and OM_1 on the side view where OM and ON

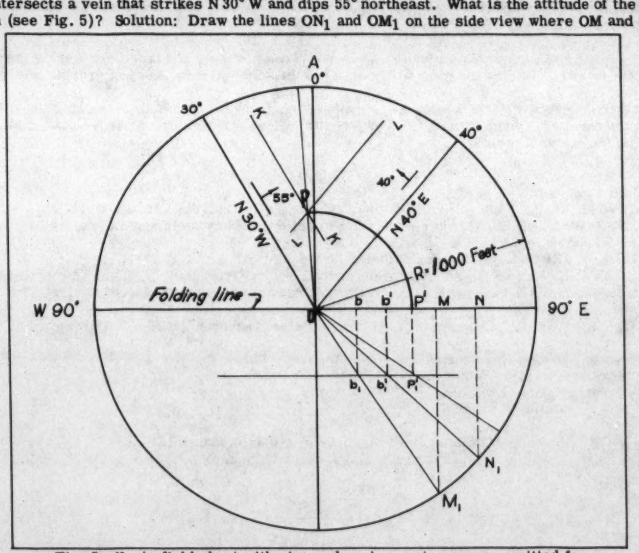


Fig. 5--Basic field sheet with sine and cosine vector curves omitted for clarity in the demonstration of the solution of fourth problem

are the cosine vectors for the true dip 55° northeast and 40° northwest respectively and the angles EOM_1 and EON_1 are 55° and 40° respectively. At a 300-ft depth from the folding line WOE, let us draw a horizontal plane whose side-view projection is line $b_1\ b_1^1$. The points b and b^1 on the plan view are the projections of the points b_1 and b_1^1.

The intersection of the lines KK and LL drawn parallel to the lines N 30° W and N 40° E respectively, and at the distances equal to Ob and Ob^1 respectively, is a point P which is at the depth of 300 ft. The line OP is the line of the intersection whose true strike equals N 5° W approximately.

By rotating OP until the line coincides with the OE line and projecting point P^1 on the $b_1\ b_1^1$ line, point P_1^1 is obtained. By drawing a straight line between O and P_1^1 until it intersects the side-view circle, the attitude of the intersection line can be obtained with the use of a cosine curve or a protractor. The inclination of this line is approximately equal to 30°

Summary and conclusions--A plan view and two side views of the orthographic projection can be conveniently expressed diagrammatically. Preliminary plotting of the azimuths of various apparent strike lines and of the cosines of true and apparent dips along the corresponding strike lines on Figure 4 greatly simplifies the graphical solutions of various field problems commonly met in structural geology.

For relatively low true dips, the use of the sine curves is preferable to that of cosine curves. Therefore, for true dips less than 30°, the sines of true and apparent dips have been evaluated and plotted on Figure 4.

For many geologic field problems, the use of two projections, that is, a plan view and a side view, is sufficient. In certain special cases, however, the use of both side views will be found convenient.

Figure 4, a few pencils, a straight edge or a scale, a compass, and a sheet of transparent paper are the only necessary tools for the solution of various field problems usually encountered in structural geology.

Closer spacing of azimuth markings on the circles, cosine and sine lines (let us say at two-degree intervals) on the diagram will increase appreciably the accuracy of graphic interpretations.

Acknowledgment--We would like to express our thanks to Ralph C. Orlansky, James Brandt, and Frederick E. Nevin of the Missouri School of Mines and Metallurgy, University of Missouri, for their helpful suggestions.

References

BECKWITH, R. H., Fault problems in fault planes, Bull. Geol. Soc. Amer., v. 58, pp. 79-108, 1947.
BUCHER, WALTER H., The stereographic projection, a handy tool for practical geology, J. Geol., v. 52, no. 3, pp. 192-212, May 1944.
FISHER, D. JEROME, Studies for students, J. Geol., v. 49, no. 3-4, 1941.
MACELWANE, JAMES B., Stereographic method of Dr. Klotz, Bull. St. Louis University, 1912.
MACELWANE, JAMES B., and F. W. SOHON, Introduction to theoretical seismology, St. Louis University, 1936.
NEVIN, CHARLES M., Principles of structural Geology, John Wiley, 1949.

Geology and Mining Engineering Departments,
Missouri School of Mines and Metallurgy,
University of Missouri,
Rolla, Missouri

(Communicated manuscript received March 16, 1951;
open for formal discussion until May 1, 1952.)

REPORT OF THE COMMITTEE ON INFILTRATION, 1950-1951

L. L. Harrold, Chairman

1951	1952	1953
S. W. Jens	F. L. Duley	Don Kirkham
A. P. Mazurak	James N. Luthin	Leon Lassen
Donald E. Whelan	Harold C. Troxell	Leonard Schiff

Reports which have been received from most of the Committee members are presented below in abstract. Full manuscripts of the separate reports are on file in the office of the Union.

E. S. Bliss, C. E. Johnson, and Leonard Schiff (submitted by Leonard Schiff, U. S. Soil Conservation Service Research, Bakersfield, California)--The following papers have been prepared for publication.

MUCKEL, D. C., Research in recharging ground-water supplies by spreading, mimeographed, presented at meeting of Amer. Soc. Civ. Eng., Los Angeles, Calif., April 26, 1950.

BLISS, E. S., and C. E. JOHNSON, Factors involved in ground-water replenishment, presented at meeting of Amer. Geophys. Union, Fresno, Calif., February 1951.

BLISS, E. S., C. E. JOHNSON, and LEONARD SCHIFF, Report on cooperative water-spreading study with emphasis on laboratory phases, August 1948-December 1950, completed March 1951, to be mimeographed.

These studies pertain to infiltration of water in definite spreading areas with the primary interest of replenishing ground-water supplies to meet irrigation requirements. It is the purpose of the Hydrologic Laboratory at Bakersfield to determine causes for the decline in infiltration capacity and the effects of various treatments on water and soil properties in increasing and sustaining infiltration capacity; to study methods to achieve similar effects through simpler or more economical means; and to isolate certain factors for study to determine their importance. The influences of dispersion, entrapped air, and biological activity on infiltration are being observed under different treatments. Cotton-gin trash or vegetation such as Bermuda and Paragrass have beneficial effects on infiltration rates. The spread of the saturated zone beyond the periphery of the spreading pond is being observed.

Future work also contemplates the study of present and new treatments. Treatments that will receive attention are those that increase infiltration capacities and have a cash return, such as a hay or forage crop. Extracts are being tried, as they may represent a simple and possibly an economical treatment of water. The use of stabilizing agents is also being considered. Fundamentals involved are studied so that the effects of treatments may be understood. Such an approach may lead to the development of treatments in various localities to achieve desired results.

Leon Lassen (U. S. Forest Service, Washington, D. C.)--At the Central Piedmont Branch of the Southeastern Forest Experiment Station, laboratory determinations are being made of percolation rates of saturated "undisturbed" soil samples from field areas in different cover. Daily soil-moisture observations are obtained in fields of: bare, poverty grass-button weed, broom sedge, ten-year planted loblolly pine, 40-year short-leaf pine, and 60-year mixed pine-hardwood. Interception and stream flow are measured at the forest sampling sites. Good correlations have been found between non-capillary pore space and percolation rates. Highest percolation rates are being found in old-growth hardwoods.

Three studies at the Coweeta Hydrologic Laboratory are summarized below.

(1) Woodland grazing has a damaging effect on the total porosity and permeability of forest soils. The effect is more noticeable at the two- to four-inch depth than at the zero- to two-inch depth. Permeability at this depth in the Cone-Hardwood area was reduced 91 per cent by cattle trampling. As the cattle spent less time in the pine-oak areas the reduction in permeability at the two- to four-inch depth was negligible.

(2) Steep agricultural land of 23 acres in mixed cover is used to study summer flood source areas. Infiltration rates (without raindrop action) showed that the trampled pasture was less capable of absorbing storm rainfall than any other agricultural areas.

(3) Abandoned cornland covered with native herbaceous and shrubby vegetative growth had high infiltration rates (3.0 in/hr) until trampled by cattle. After 15 animal-use days per acre on this wet clay-loam soil, this rate reduced to 1.5 in/hr. After 30 days the infiltration rate was 0.62 in/hr.

Infiltration studies at the Intermountain Forest and Range Experiment Station include a series of exploratory tests on desert grass range in southeastern Utah and analyses of data collected. Type F infiltrometer tests in Idaho and Utah are showing that ground cover (plants and litter) are the main site characteristics affecting infiltration and runoff where much of the ground is covered. Type FA infiltrometer tests on sparsely covered (30 per cent) desert grass range show soil texture to be an important factor affecting infiltration, runoff, and soil loss. Analyses are being made of 66 Type F and FA infiltrometer test plots in Wyoming, Utah, and Nevada to evaluate the effect of such factors as burning, grazing, and reseeding.

Infiltration studies were made by the Buckeye Branch of the Central States Forest Experiment Station at 14 different places in Ohio. Water was poured from a flask onto the soil within a steel casing inserted into the soil. Tests showed that (a) small changes in porosity resulted in large changes in infiltration rates, (b) soil texture, as it affects size of pores, influenced infiltration rates, and (c) soil moisture in excess of moisture equivalent apparently blocks some pores and affects infiltration rates.

A series of studies was conducted by the Northern Rocky Mountain Forest and Range Experiment Station, Missoula, Montana, to determine the effect of slash disposal in undisturbed and cut-over areas of a 160-year Lodgepole Pine forest. Infiltration values were obtained in (a) natural surface green forest, (b) natural surface cut-over land, (c), burned, and (d) scarified.

The Pacific Northwest Forest and Range Experiment Station is making infiltration determinations from laboratory permeability runs on field soil samples (undisturbed). Data are used in flood-control studies. The Southern Forest Experiment Station conducted a few infiltration studies using soil core samples obtained near Jackson, Tennessee, and in northern Mississippi. Infiltration studies made by the Southwestern Forest and Range Experiment Station have been confined to the Workman Creek area in Arizona, elevation 6600 to 7700 ft in pine-fir forest type. The Type FA infiltrometer was used.

A recent description of the operation and maintenance of the Type FA infiltrometer has been prepared by E. J. Dortignac for early release by the Rocky Mountain Forest and Range Experiment Station.

D. E. Whelan (U. S. Forest Service, Northeastern Forest Experiment Station, Upper Darby, Pennsylvania)--Field observations of climatic factors, snow depth, soil moisture, frost depth, rates of flow, and land use are being made at six experimental forests in New England, New York, and Pennsylvania. A laboratory study of soil freezing, type of frost, soil moisture, organic matter, and rates of infiltration is carried on along with field observations. The following papers have been recently prepared.

TRIMBLE, G. R., JR., C. E. HALE, and H. S. POTTER, Effect of soil and cover conditions on soil-water relationships, Station paper 39, February 1951.

WHELAN, D. E., L. E. MILLER, and J. B. CAVALLERO, Determination of surface runoff by routing infiltrated water through the soil profile.

A. P. Mazurak (Nebraska Agricultural Experiment Station, Lincoln, Nebraska)--Infiltration measurements were made on the 38-year-old rotation and continuous crop systems at the Scotts Bluff Station. Physical properties of the soils to a depth of six feet are being determined for correlation with infiltration data. No conclusions are yet available.

F. L. Duley (U. S. Soil Conservation Service Research, Lincoln, Nebraska)--Infiltration studies are being made on claypan soils of Nebraska by Paul E. Fischbach and F. L. Duley. Large plots are used so that the intake rate of the claypan can be measured. Soil-moisture observations to a depth of ten feet indicate that large amounts of water passed entirely through the claypan layer, the minimum rate being 0.05 in/hr. The amount of water stable aggregates had no apparent correlation with permeability. Soil texture appeared to be more important. Non-capillary porosity influenced infiltration.

T. M. McCalla is studying the effect of micro-organisms on percolation of water through short tubes of soil in the laboratory. The addition of organic matter to the soil decreased percolation under submerged conditions, but it increased percolation after drying and stirring.

James N. Luthin (California Agricultural Experiment Station, Davis, California)--Field studies on the distribution of hydraulic head around a tile line have been in progress since De-

cember 1950. The drained area is in an area of seepage from the Sacramento River and the water is moving upwards in the soil. One hundred and forty-four piezometers consisting of 3/8-inch pipe were driven to three depths below the soil, three, five, and ten feet.

Field studies have been instituted in the Susanville area, California, to study the seepage from an irrigation canal. Piezometers are being used in the study.

A paper entitled "Numerical analysis of flow through aquifers towards wells" by James N. Luthin and V. H. Scott was presented by James N. Luthin at the Pacific Coast Regional Meetings of the American Society of Agricultural Engineers in February 1951. Numerical solutions of the cylindrical form of Laplace's equation were obtained for several flow problems encountered in the field. The treatment included layers having different permeabilities.

R. H. Burgy and V. H. Scott of our Division of Irrigation are engaged in the construction of an infiltrometer for use in the field. A modified North Fork infiltrometer has been made and field trials are being run.

Laboratory tests have been run by Scott and Burgy to investigate the effect of the ash of burned brush in infiltration rates. Undisturbed cores have been used in this study.

Lloyd Doneen and Delbert Henderson have made a preliminary investigation of the relationship between soil density and infiltration rates. Doneen is continuing his research on the effect of sodium in irrigation water on the rate of infiltration.

F. J. Veihmeyer, assisted by R. H. Burgy, is continuing the long-time experiments on the effect of brush burning on the hydrology of range land. Some new watersheds have been added to those already under study.

L. L. Harrold (U. S. Soil Conservation Service, Research, Coshocton, Ohio)--The following infiltration papers have been prepared for presentation at the August 1951 meeting of the International Union of Geodesy and Geophysics at Brussels, Belgium.

LASSEN, LEON, and HOWARD W. HULL, Infiltration and the use of the infiltrometer.

SCHIFF, LEONARD, Infiltration - a tool for the evaluation of the effect of land use on runoff.

HARROLD, L. L., Infiltration as affected by surface sealing.

Infiltration curves are being obtained from rainfall and runoff records on natural watersheds in rotation crops and permanent covers of grass and trees. Soil moisture and soil physical data are also gathered for correlation with infiltration. In an exploratory study, infiltration curves derived from small single-crop watersheds were used to derive values of surface runoff for larger mixed-cover watersheds. These values were then checked against the measured flow from this larger basin and found to be in reasonable agreement. More study is needed on this phase of the use of derived infiltration curves. A paper describing this study was prepared for publication in the TP series of the U. S. Soil Conservation Service, Washington, D. C., as follows.

LEONARD SCHIFF, Hydrology of rates and amounts of surface runoff from single and mixed-cover watersheds, SCS-TP-104-TP, 1951.

The results of studies of infiltration curves for specific types of land cover and for different soil-moisture conditions were summarized for use in analyzing the hydrologic performance of watersheds. This summary appears in

SCHIFF, LEONARD, Hydrology of surface supplies to runoff, U. S. Soil Conservation Service, Washington, D. C., SCS-TP-90, February 1951.

Soil moisture, as it affects air-space porosity in the soil profile, was found to be a significant factor influencing infiltration rates. This relationship serves as a useful tool to designate the placing of the infiltration curve over the graph of rainfall rates to derive values of excess rainfall (supplies to runoff). The application of this procedure and its use in deriving runoff values from different precipitation patterns, advanced and retarded type storms, is given in the following publication.

SCHIFF, LEONARD, Surface runoff supply estimates based on soil-water movements and precipitation patterns, U. S. Soil Conservation Service, Washington, D. C., SCS-TP-86, October 1949.

In Region II of the Soil Conservation Service as reported by H. N. Holtan of Blacksburg, Virginia, infiltration observations are becoming useful tools in (1) deriving estimates of benefits from flood reductions due to changes in infiltration rates resulting from land treatment; (2) estimating

runoff based on vegetal cover and soil permeability for flood-peak values needed in hydraulic designs as well as total runoff values needed in problems of farm water-supply systems; and (c) handling irrigation problems involving infiltration capacity rates, water-holding capacities of the soil, and transmission rates through the soil.

U. S. Soil Conservation Service,
Research Station,
Coshocton, Ohio

(Manuscript received May 2, 1951; presented at the Thirty-Second Annual Meeting, Washington, D. C., April 30, 1951; open for formal discussion until May 1, 1952.)

Transactions, American Geophysical Union Volume 32, Number 6 December 1951

AN IMPROVED SAND CLASSIFIER

H. L. Uppal and Gajinder Singh

Abstract--An improved sand classifier for quick and accurate analysis of sand particles is based on the principle that sand particles, when dropped across a horizontal stream of air flowing at a constant speed, separate and distribute themselves according to their sizes. The apparatus is accurately calibrated with known grades of material varying from 0.64 to 0.08 mm so as to give directly the size distribution of a sample, thus avoiding lengthy arithmetical calculations. From 100 to 125 samples can be analyzed in a day.

Introduction--Sediment surveys of the canal system of Punjab Province started in 1935-36. In each survey a large number of samples had to be collected from main lines, branches, and distributaries, and analyzed to construct their size-distribution curves. The need for a quick and accurate apparatus for sediment analysis was greatly felt. In order to meet this demand, a sand classifier was developed using air as a medium instead of water [OTTO and ROUSE, 1939]. The essential advantages of this type of sand classifier are:

(1) It gives the size-distribution curve directly, thus avoiding lengthy arithmetical calculations.
(2) From 100 to 125 samples can be analyzed in a day.
(3) The analysis is accurate.

The sand classifier utilizes the fact that the particles, when dropped across a horizontal stream of air, separate and distribute themselves according to their sizes, that is, according to the diameter of their equivalent spheres having the same density and velocity of fall. The heavy particles fall near and the light ones fall farther away.

Description of the apparatus--The sand classifier comprises an electric blower and an experimental tank with an air tunnel and collecting chambers.

A blower, coupled to an electric motor, sends out a continuous current of air at a uniform rate. The speed of air is maintained by regulating the speed of the motor through a system of rheostats. The blast of air spreads out as it enters the glass-sided stilling chamber. The turbulence caused in the stream because of expansion is stilled by passing it through a set of honeycombs designed for the purpose. It becomes further smoothed as it enters the lead chamber, where the width of airway contracts from 2.0 inches to 1/4 inch.

The experimental tank is made of two glass plates 4.0 × 3.0 ft × 5/8 inch. The upper 1.5 ft is used as an air tunnel through which a uniform current of air flows in a horizontal direction. The bottom of the air tunnel consists of a grid whose spacings have been determined experimentally. The grid is so designed as not to allow any particle to accumulate on its upper edges. The equispaced collecting chambers are calibrated to read directly the percentage by weight of the collected particles.

The bottom of the collecting chambers is detachable so that the sample can be readily taken out after analysis.

A specially designed silt-dropping funnel is fitted at the top right corner of the air tunnel. It has a shutter fitted at its bottom which permits the silt to drop in a thin sheet across the section.

A centigrade thermometer is provided in the airway at the end of the tunnel which gives the temperature of the outgoing air. A photograph of the collecting chamber is shown in Figure 1.

Procedure--A thoroughly air-dried sand sample is screened through a sieve so as to remove foreign matter. A weighed quantity of sand is put in the funnel. After adjusting the speed of the blower, the shutter of the funnel is opened. The particles separate and collect in their respective collecting chambers at the bottom. A direct size-distribution curve is obtained as shown in Figure 1.

Fig. 1--View of the collecting chamber

Calibration of the sand classifier--The calibration of the apparatus is most important and is done by the following method. A dried and screened sample is introduced, and particles sorted by the sand classifier are collected at about 15 different points at the bottom of the tank. Diameters of more than 1000 particles collected at a single point are observed under a high-power microscope both along the x-axis and the y-axis. A mean of these observations gives the mean diameter of the particles falling at that point. The horizontal distance of this point from the dropping point is measured accurately and the observations repeated several times. Finally, a curve is plotted using the mean diameter of the particles and the horizontal distance traveled by them. This gives the calibration curve of air sand classifier. It is shown in Figure 2.

Particles of known diameter are collected to different heights in a collecting chamber. The height to which they collect is recorded and the particles are weighed. A curve is plotted between

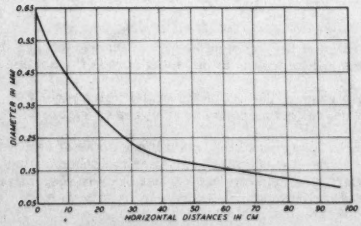


Fig. 2--Calibration curve of the air sand classifier

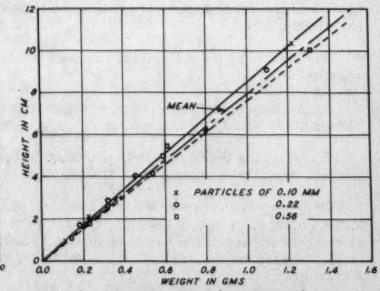


Fig. 3--Relation of weight of particles to height of particle column

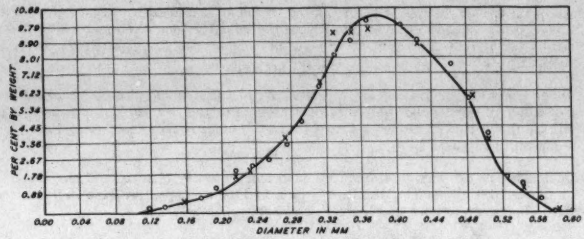


Fig. 4--Reproducibility of size-distribution curve using the same sample

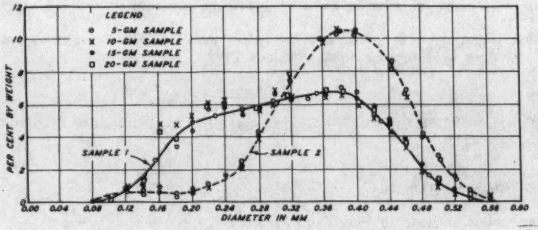


Fig. 5--Reproducibility of size-distribution curve for two samples using different quantities of sample

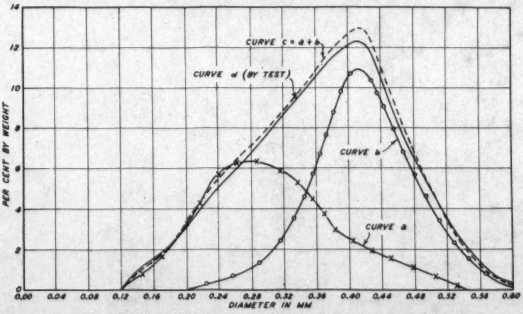


Fig. 6--Reproducibility of size-distribution curve, comparing algebraic sum of two curves with a mixed sample

the weight and the height of the particles. This operation is repeated with particles of various diameters. A plot of the observations is shown in Figure 3. Finally, a mean of all these curves is prepared and from this curve the weight per centimeter height of particles is calculated. Knowing this and the total weight of the sample, percentage by weight per centimeter height of collecting chambers is obtained.

In order to examine the accuracy of the sand classifier, tests on reproducibility were carried out as follows. A weighed quantity of a well-mixed sample is introduced and size-distribution curve obtained. The same sample is put in again to see whether or not the size-distribution curve reproduces itself. From a large number of tests carried out it was shown that the curve is correctly reproduced. One case is shown in Figure 4.

A known quantity of a sample was introduced in the sand classifier and its size-distribution curve obtained. In the second experiment, double the quantity was taken and a size-distribution curve plotted by taking half the observed value of percentage weight of particles collected in different chambers.

Next, three times the original quantity was dropped and a curve plotted by taking one-third the observed values of percentage weight of particles collected in different chambers. It was found that all the three curves closely agreed with each other. This test, using two different samples, is shown in Figure 5.

Equal quantities of two samples, one fine sand and the other a little coarser, were taken. They were introduced in the sand classifier in turn and their respective size-distribution curves were obtained. These are shown in Figure 6 (see curves a and b).

A curve was then plotted by taking the algebraic sum of these curves (curve c). Then a mixture of these two samples was introduced by taking equal quantities of each, and the size-distribution curve so obtained was plotted as shown in Figure 6 as curve d. This curve agrees well with the algebraic-sum curve, confirming the accuracy of the apparatus for sand analysis.

The results obtained with the air sand classifier were compared with those obtained with the nest of sieves. They were found correct within ± 4.5 pct.

Reference

OTTO, G. H., and HUNTER ROUSE, Wind-tunnel classifier for sand and silt, Civil Eng., v. 9, pp. 414-415, July 1939.

Hydraulic Research Station,
Malakpur (Pathankot), India

(Communicated manuscript received November 3, 1950, and, as revised, May 2, 1951; open for formal discussion until May 1, 1952.)

Transactions, American Geophysical Union Volume 32, Number 6 December 1951

A METHOD FOR COMPARING THE FLOW FROM A PAIR OF EXPERIMENTAL WATERSHEDS

B. C. Goodell

Abstract--This paper describes briefly a method developed to predict the annual stream flow of one experimental watershed from that of another. The watersheds are not similar in size or in topographic characteristics. They are at similar elevations. It is possible to predict the stream flow for selected months or for natural segments of the hydrograph. Likewise, the shape of the hydrograph and the total volume of flow can be established. Errors of prediction are discussed as well as the precision required to determine the effects of treatment which might be applied to an experimental watershed.

Introduction--Watershed-management research deals with the effects on stream flow of some type of land treatment such as timber harvesting or grazing by livestock. One method of measuring these effects requires the comparison of stream discharges from two or more similar watersheds. A preliminary study is made which results in the ability to predict the flow of one stream from knowledge of the flow of the other. The treatment to be tested is then applied to one watershed and the subsequent difference between actual flow and predicted flow is conclusive evidence of the treatment effect.

There are various ways by which the flow relationships of two streams can be studied and quantitatively expressed. The problem still remains, however, as to how to do this most effectively for any particular watershed under study and for the specific objectives to be reached. One procedure for comparing the flow of two streams and determining the necessary duration of the preliminary or calibration period of study has been described elsewhere [WILM, 1949]. This paper describes another method which seems to be more flexible. The method has been tested on only one pair of watersheds and it is this specific test which will be described.

Description of watersheds--At the Fraser Experimental Forest in north-central Colorado, six years of stream-flow records have been obtained for two experimental drainages, namely, Fool Creek of 710 acres, and East St. Louis Creek of 2,430 acres. It is the object of the experiment to harvest the timber consisting of lodgepole pine, Engelmann spruce, and alpine fir on the Fool Creek watershed and determine the effect this land treatment has on stream flow. The East St. Louis watershed will be maintained as a check. Stream-flow records extend from approximately April 20 to September 25 of each year, the period when 85 per cent of the stream flow occurs from snow melt and summer rains. Both watersheds are above 9,500 ft in elevation and are adjacent to one another.

The rise in the hydrographs of the two watersheds is caused by rapid spring snow melt with peak flows occurring from June 12 to 22. The rise in both streams is well correlated. After the peak is reached, the receding flow is more rapid for Fool Creek than for East St. Louis Creek. This latter difference may lie in the terrain characteristics of the watersheds rather than differences in size. East St. Louis Creek watershed contains a large area of glacial till, where glacial "terraces" across the slope tend to hold back snow-melt waters, and several areas of talus. Fool Creek watershed, on the other hand, has none of these vestiges of glaciation. Average annual stream flow for Fool Creek amounts to nearly 13 inches of depth, while for East St. Louis Creek it is about 16 inches.

Description of method--Using the records of both streams for the period April 20 to September 25 during the six years, the problem was one of developing a procedure for estimating the flow of Fool Creek (to be treated) from that of East St. Louis (to remain untreated) and determining the error of estimate of the mean values.

Inspection of the annual hydrographs of the two streams revealed that the two streams rose and fell nearly simultaneously in minor as well as major variations, but that the relative magnitudes of the peaks and troughs change with the season of flow. Furthermore, this change seemed

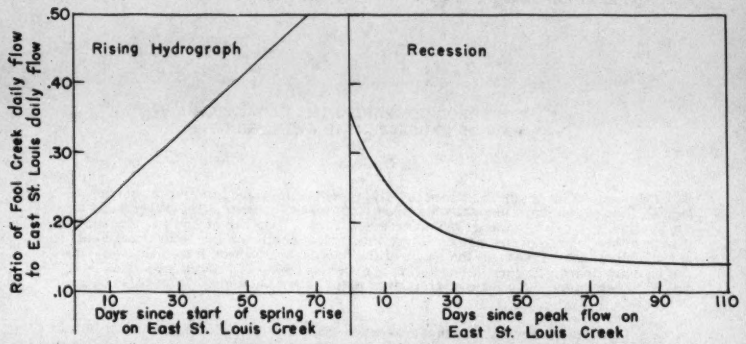


Fig. 1--Ratio of Fool Creek to East St. Louis Creek daily flow during rising hygrograph and recession (six-year average)

to be in the nature of a trend associated with elapsed time since start of the spring rise. This trend is of major significance as it led to the use of variable ratios in estimating the flow of one stream from another.

The flow of Fool Creek for each day of record (897 days) was divided by the corresponding flow of East St. Louis Creek. These ratios were plotted against the days since the start of the spring rise until the peak was reached on the one hand (rising hydrograph) and on the other the ratios were plotted against the days after the peak (receding hydrograph) (see Fig. 1).

It might have been expected, from the apparent similarity of the watersheds, that the ratios would show no trend with time. Instead, they grouped around a rapidly ascending straight line on the rising side of the hydrograph and around a falling curved line on the recession side. During the rise of the streams, Fool Creek rises much faster than East St. Louis Creek. The ratio between the two increases from 0.2 to about 0.5 at the time of the spring peak. During the recession the ratio falls to less than 0.15.

East St. Louis Creek has almost 3 1/2 times as much watershed area and about 1-1/4 times as much water yield per unit of area as does Fool Creek. It would have been expected to flow approximately 4 1/3 times as much as Fool Creek throughout the season. Actually, at the beginning of the rising hydrograph it flows five times as much and at the peak only twice as much as Fool Creek. On the recession it flows from three times as much at the beginning to seven times as much at the end of the record period (late September).

Comparison of actual and estimated flow--The ratio for a given day as read from the average lines (Fig. 1) multiplied by the flow of East St. Louis Creek for the same day gives an estimated flow for Fool Creek for that day. Following this procedure, the flow of Fool Creek was estimated for each day during the spring and summer periods of all six years of record. The effectiveness of the method for predicting daily flows is shown in Figure 2.

The three years which were chosen for illustration represent extremes in the character of annual flow. The year 1943 was one of late snow melt, a late peak and a short recession, a year of best agreement with 0.8 per cent error; 1945 was a year of early snow melt, an early peak and a long recession interrupted by summer rains, a year of worst agreement with 14.5 per cent error; 1947 was an average year for the rise and recession but with an unusually variable flow during the spring flood, a year of average agreement with 4.4 per cent error. Even with these hydrographic differences, the technique gives a good fit of estimated to actual flow for all years.

Through summations of the daily flows the new technique was used to estimate the flow of each year of record. Table 1 presents the comparison between actual and estimated yearly flows

Table 1--Summary of actual and estimated flow of Fool Creek by years

Year	Actual flow	Estimated flow	Difference		Standard error of the mean expected 19 times out of 20		
	ac ft	ac ft	ac ft	pct	ac ft	inch	No. yrs
1943	748.07	754.06	- 5.99	0.8	149.75	2.53	1
1944	473.24	516.70	- 43.46	9.2	105.91	1.79	2
1945	621.51	711.38	- 89.87	14.5	86.46	1.46	3
1946	576.58	540.57	+ 36.00	6.2	74.88	1.27	4
1947	866.97	829.22	+ 37.75	4.4	66.97	1.13	5
1948	644.74	584.42	+ 60.32	9.4	61.15	1.03	6
Total	3,931.11	3,936.35	273.39	...	.....	.....	..
Average	655.19	656.06	45.57	7.0	.....	.....	..

Correlation coefficient for six years of records = 0.91, highly significant.
Standard error of estimate of the mean (655.186 ac ft) = 23.8 ac ft.
Standard deviation of estimate for any year = 58.2 ac ft or approx. one inch of depth.

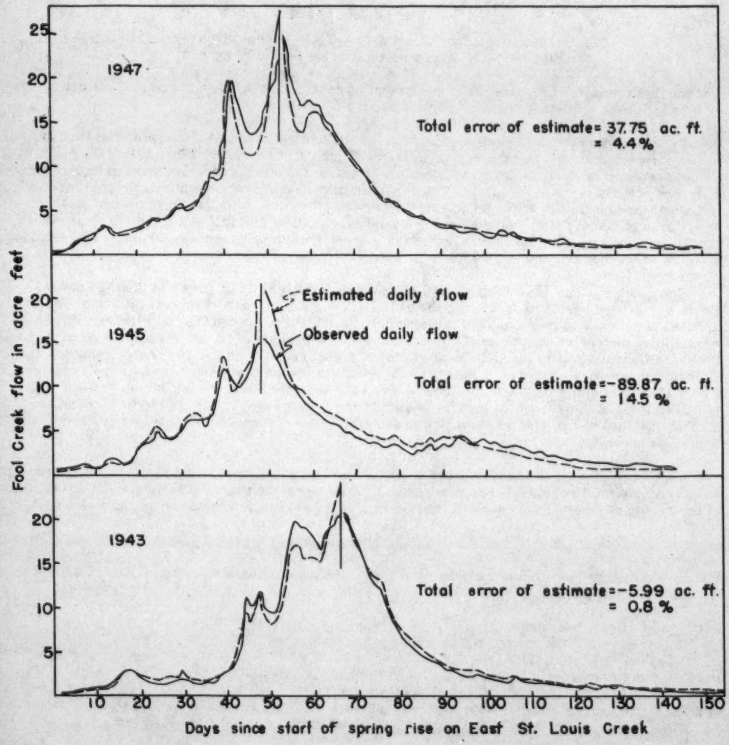

1947
Total error of estimate= 37.75 ac. ft.
= 4.4%
1945
Estimated daily flow
Observed daily flow
Total error of estimate=-89.87 ac. ft.
= 14.5 %
1943
Total error of estimate=-5.99 ac. ft.
= 0.8 %
Fool Creek flow in acre feet
Days since start of spring rise on East St. Louis Creek

Fig. 2--Comparison of estimated and observed daily flow of Fool Creek

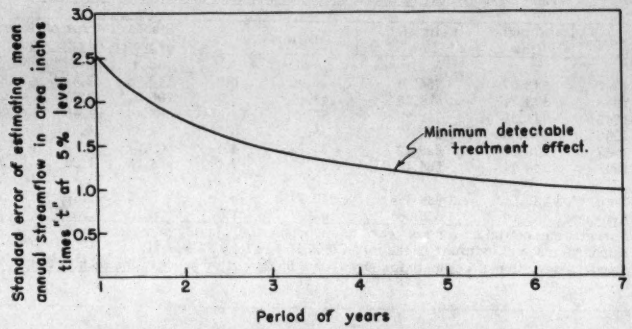


Fig. 3--Standard error of estimating mean annual stream flow at five per cent level with increasing period of record

and the discrepancies by years. The coefficient of correlation between actual and estimated flows is given with the statistics pertaining to the errors of estimate.

Precision of method--The precision of the method of estimating the mean annual flow of Fool Creek for periods of years up to six is shown in Figure 3. The error of estimating the mean with 95 pct certainty is equal to the standard error of estimate times Student's t and is plotted against different periods of estimated flow. The resultant curve represents the minimum treatment effect on annual stream flow that can be detected under the precision of the two-stream comparison. Deviations of actual from predicted mean annual stream flow that fall below the curve should be attributed to chance effects. Deviations which exceed the curve values can properly be associated with the watershed treatment applied.

Conclusions--The described method of relating the flow of Fool Creek to that of East St. Louis has proved useful in predicting the annual flow of Fool Creek. However, its chief recommendation over the simpler method of using only annual flows to express the relations lies in its adaptability to predicting stream discharge for shorter periods of time. Thus, with respect to the present illustration, it is possible to predict the flow of Fool Creek for any chosen month of the year or for a natural segment of the annual hydrograph such as the rising limb or the recession limb. By establishing the past relations between the two streams for each day of the year and tying the ratio of their flows to natural breaks in the hydrograph, it is possible to predict the short-term flow of one stream from that of the other even though the flow ratios vary widely during a year's course.

Another advantage of the procedure is that it enables prediction of the shape of the hydrograph as well as the total volume of flow represented. It is therefore useful in testing whether the timing of the spring peak will have been affected by an induced change in vegetation on the watershed.

Reference

WILM, H. G., How long should experimental watersheds be calibrated?, Trans. Amer. Geophys. Union, v. 30, pp. 272-278, 1949.

Division of Forest Influences,
Rocky Mountain Forest and Range Experiment Station,
Fort Collins, Colorado
(Now with the Engineering Department, Johns Hopkins University, Baltimore, Maryland)

(Manuscript received February 19, 1951; presented at the Thirty-Second Annual Meeting, Washington, D. C., May 1, 1951; open for formal discussion until May 1, 1952.)

Transactions, American Geophysical Union Volume 32, Number 6 December 1951

DISCUSSION OF

"A COMPARISON OF SEVERAL HEAT AND MASS TRANSFER NETWORKS OF INTEREST IN WATER CONSERVATION"
by H. F. POPPENDIEK and M. TRIBUS

[Trans., v. 32, pp. 49-56, 1951]

Ernest R. Anderson and J. J. Marciano (U. S. Navy Electronics Laboratory, San Diego, Calif.) and G. E. Harbeck, Jr. (U. S. Geological Survey, San Diego, Calif.)--The use of electrical networks to describe heat- and mass-transfer problems is an interesting concept and undoubtedly will be of considerable value in future water-loss investigations, provided the processes involved can be represented, electrically, with sufficient accuracy.

Although it is true that errors in measurement of water-surface temperature may arise when there are steep gradients in the fluid, such a temperature profile will not be associated with high evaporation rates, as implied by Poppendiek and Tribus. High evaporation is associated with appreciable wind and a resultant stirring or mixing of the upper part of the fluid. Hence the possibility of making large errors in water-surface temperature measurements during periods of high evaporation rates are minimized. The results of the first three months of operation at Lake Hefner, Oklahoma City, Okla. [ANDERSON, ANDERSON, and MARCIANO, 1950] indicate that any error in evaporation computed from either the mass-transfer or the energy-budget equations due to errors in the measurement of the water-surface temperature are insignificant when total evaporation over a 24-hour period is considered.

The measurement of water-surface temperature by "dragging a light balsa-wood float, with an attached thermocouple under it, over the lake surface" as suggested by Poppendiek and Tribus, does not appear practical because of the mechanical mixing induced by the float. This mixing would certainly extend to several centimeters below the surface. In connection with the Lake Hefner evaporation studies, water-surface temperature is being measured by a thermocouple supported by three small can buoys connected by a light framework. The thermocouple is adjusted to bob in and out of the water under light-wind conditions. Checks of the temperature as measured by this method indicate that the actual surface temperature is being measured to within 0.1° to 0.2°C.

The writers are unaware of any inherent assumption that the energy-budget method requires that the energy be absorbed entirely at the lake surface. It is immaterial where the energy is absorbed provided that the change in energy stored in the body of water over a given time interval can be measured with sufficient accuracy. Preliminary results of the Lake Hefner studies indicate that this evaluation is possible.

In the last sentence of their paper Poppendiek and Tribus state: "Until methods of measurement for either the water side resistance or the water side energy flux are available, the energy methods cannot be used for accurate prediction of evaporation rates from lakes." This apparent indictment of the energy budget is interpreted to mean that at this time it is impractical to simulate the natural processes by electrical networks. The analysis of the data from the Lake Hefner study with respect to the determination of evaporation utilizing the energy-budget equation is not complete enough to warrant the publication of any conclusions. However, the preliminary indications are that the application of this equation is a practical and theoretically sound means of determining evaporation from a free water surface.

Reference

ANDERSON, E. R., L. J. ANDERSON, and J. J. MARCIANO, Interim report: Lake Mead water-loss investigations--a review of evaporation theory and development of instrumentation, U. S. Navy Electronics Laboratory Report 159, February 1950.

H. F. Poppendiek and M. Tribus (Authors' closure)--The authors regret the use of the word "electrical" in the abstract for, while the electrical analog is an important tool in solving diffusion

problems, it was intended in this paper to emphasize the use of network representation for field problems. By presenting representative networks the authors hoped to focus attention on areas in which measurements are needed.

Reference to Figure 6 should clarify the authors' remarks concerning steep temperature gradients near lake surfaces. Application of the first law of thermodynamics (or Kirchoff's circuit law to the thermal flux) at the surface of the lake yields the result that when evaporation occurs at the lake surface there must be energy flux from above, below, or both. High evaporation rates are also associated with large vapor-pressure differences between the water surface and the air (the mass-transfer driving force). Such differences arise when water-surface temperatures are high (under strong solar radiation conditions); under these conditions high water-temperature gradients can exist in the water layers near the surface.

The difficulties suggested likely to occur with the balsa wood float did not occur in practice. The measurements were carried out during classified wartime research in 1945. The balsa float extended only a millimeter or two into the water and the thermocouple was located at the float bottom-water interface near the front of the float. The mixing layer, caused by the moving float, at this point was estimated to be about a millimeter thick.

The "bobbing-floating" thermocouple for obtaining lake surface temperatures should be least accurate when the interface is warmer than either the air above or water beneath. The accuracy of 0.1°C represents an enviable technique for field measurements.

The comments of the discussors indicate a difference in point of view concerning the study of heat and mass diffusion from lakes. Our interest lies in the understanding of the details of these instantaneous transfer processes; we await the results of the Lake Hefner study with great interest.

DISCUSSION OF

"VARIATIONS IN STORM RAINFALL OVER SMALL AREAS"
by RAY K. LINSLEY and MAX A. KOHLER

[Trans., v. 32, pp. 245-250, 1951]

Walter T. Wilson (44 Loma Road, Redwood City, Calif.)--As the authors of this informative and instructive paper state, their study is in no way comprehensive. Many readers will wish to examine additional measures and relationships. The authors have been kind enough to supply this reader with a table of the storm rainfall data on which they based their analyses, and have thus enabled him to present two additional relationships.

In Figure 7 of this discussion are plotted points, each representing by its abscissa the mean rainfall of the 55 stations for one of the 71 storms, and by its ordinate the range between the smallest and largest rainfall amounts received among the 55 stations, for the same storm. It may be observed that with most of the storms, the range exceeds the mean. If it is assumed, with 55 stations, that the standard deviation is between 20 and 25 per cent of the range, then the coefficient of

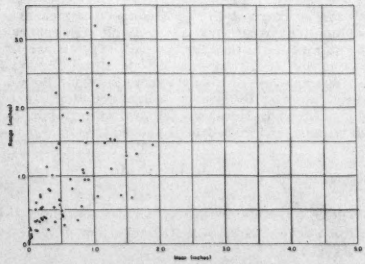


Fig. 7--Relation of range in storm rainfall to mean rainfall (55 stations)

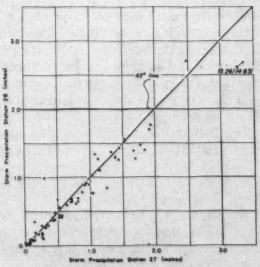


Fig. 8--Relation between storm precipitation at two adjacent stations (27 and 28)

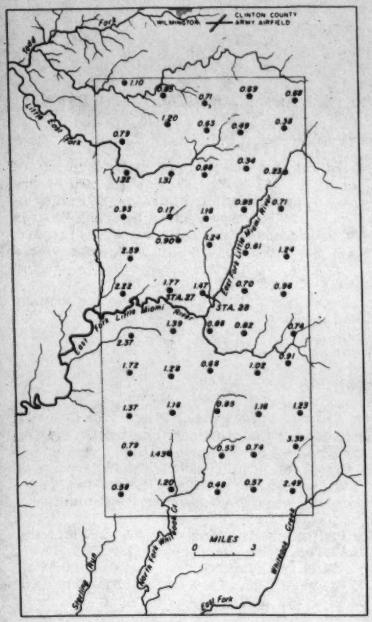


Fig. 9--Storm of August 4-7, 1947

variation may be estimated to have a value of about 0.3. There seems little doubt that in more rugged portions of the United States, even with non-thunderstorm precipitation, there would be greater areal variability of precipitation.

Another simple expression of variability is shown in Figure 8, where the values of rainfall observed at Stations 27 and 28 are plotted against each other for each storm. These stations were chosen arbitrarily for this example. They are about two miles apart, and hydrologists may consider substituting the record of one for that of the other. This substitution is relevant in such instances as choosing a site for a station, and assuming that it "represents" rainfall over a certain area, say halfway to the next station, which ordinarily is much more than two miles distant. Another instance occurs when there is a change of station location, and the question arises whether to consider the new record as an extension of that of the original station location, or whether to designate the new site "only a couple of miles away" as a new station. A quick estimate of correlation may be made by comparing the dispersion of the points (in the Y-direction), about a regression line to the dispersion of the values of the Y variable. This gives the ratio of standard error of estimate to standard deviation, which defines the correlation coefficient in the standard formula

$$r = [1 - (S_e/S_y)^2]^{1/2}$$

In this instance, a 45° line was taken as the regression line, and the correlation coefficient was computed to be about 0.96. Now how can an effective appraisal of this "high" coefficient be made? Certainly there is no question about its being highly significant, statistically. But if we think operationally, in terms of substituting the values of one station for those of the other, we must consider the fact that the standard error of estimate is nearly a third as great as the standard deviation. In other words, the variation in estimating the values of storm rainfall at Station 28, from those at Station 27, is nearly a third as great as the variation in storm rainfall itself at either station.

Figure 9 is a map on which, for each station, the values of rainfall for the storm of August 4-7, 1947, are shown. This storm was chosen because of the fairly large amounts of rainfall which occurred, and because of the high degree of areal variability of the rainfall. No attempt is made in this discussion to draw an isohyetal map, but the reader is invited to look at this map and to consider the following fact. The area covered by these 55 stations is less than the average area per precipitation station in the United States. This means that in drawing isohyetal maps in many regions where there is only one station in an area of 200 to 300 sq mi, this one station might, by chance, have any of the values shown on this map. Thus, the value of an isohyet determined by this one station might range anywhere from 0.2 to 3.4 inches.

Ray K. Linsley and Max A. Kohler (Authors' closure)--Wilson has extended the authors' analyses, which were mainly concerned with variations in computed average rainfall, to display some of the variations in rainfall from point to point. His analysis shows the wide differences in rainfall which may be observed between two adjacent points even in an area of negligible orographic effects. As he suggests, the data utilized in the study could form the basis for still further analyses. A copy of the material can be obtained from the U. S. Weather Bureau, Washington, D. C.

MINUTES OF EXECUTIVE COMMITTEE MEETING, AMERICAN GEOPHYSICAL UNION

Meeting of October 15, 1951

The meeting was called to order in the Secretary's Conference Room of the Department of the Interior (Room 5160), Interior Building, Washington, D. C., at 13h 45m, October 15, 1951 by President Walter H. Bucher. Nineteen persons were present, namely: L. R. Alldredge, K. Hilding Beij, Walter H. Bucher, Wilbur S. Burbank, James J. Capello, Felix Chayes, Harry H. Hess, Woodrow C. Jacobs, Walter D. Lambert, Walter B. Langbein, John Lyman, John Putnam Marble, Leonard Murphy, Irwin Roman, William W. Rubey, McClain B. Smith, Waldo E. Smith, Victor Vacquier, and R. Hanson Weightman.

Approval of Minutes--The minutes of the meeting of May 2, 1951 were approved as published in the August 1951 issue of the Transactions, pages 628-651.

General Secretary's Report

General Activities

Executive Committee--William W. Rubey, new Chairman of the National Research Council, succeeds Douglas Whitaker. New officers were elected by the International Union of Geodesy and Geophysics and its Associations during the summer, and as a result Howel Williams ceases to be a member of the Executive Committee while Beno Gutenberg, new President of the International Association of Seismology and the Physics of the Earth's Interior, and C.-G. Rossby, new Vice President of the International Association of Meteorology, become members of the Committee.

Financial Report--The financial statement for the fiscal year ending June 30, 1951 is in the hands of the Committee on Audit. The report shows an operating surplus of $1,787.58, and a slight increase in the Permanent Fund. Our cash balance on October 1, 1951 was $11,190.69 as compared with $9,437.40 a year ago and $5,953.93 two years ago. The Permanent Fund on October 1, 1951 totaled $3,469.82 as compared with $3,102.55 a year ago.

Membership--A summary of the membership changes since April 30, 1951 is as follows:

Membership, April 30, 1951	4740	
New members, April 30 to October 12, 1951	201	
Reactivated	4	4945
Resignations	59	
Deceased	11	
Inactive	4	
Dropped	153	227
Membership, October 12, 1951		4718

Those reported as deceased since our last meeting are as follows: Eugene A. Golomshtok, June 20, 1950; Charles V. Averill, August 20, 1950; Milton C. George, September 28, 1950; R. A. Graham, November 5, 1950; Harry L. Collins, December 30, 1950; Abd Essalam M. Hussein, _____ 1950; Mrs. Helen J. Plummer, January 11, 1951; James O. Letts, March 6, 1951; Charles S. Bennett, March 10, 1951; Walter B. Wilson, May 21, 1951; and Boris A. Bakhmeteff, July 21, 1951.

Meetings and Regionalization--The Twenty-Seventh Regional Meeting will be held in Pasadena, California, February 8-9, 1952, with the Sections of Meteorology and Hydrology definitely planning to participate. The Committee for organizing this region appointed by the President in accordance with the plan established in 1949 consists of J. W. Johnson as Chairman, Harry F. Blaney, Harold Conkling, Morris Neiburger, Robert H. Simpson, and Edward M. Vernon. Thus far the Sections of Hydrology and Meteorology are represented.

A notice regarding plans for the Thirty-Third Annual Meeting and a tentative schedule were sent out to the Executive Committee on October 5, and pertinent information will appear in the Special Announcements of the October issue of the Transactions, page 807.

Plans to participate in the Centennial of Engineering to be held in Chicago, September 11-12, 1952, are taking shape. The Committee appointed for this meeting consists of Horace R. Byers as Chairman, W. S. Hamilton, William C. Krumbein, Arno T. Lenz, Mathew L. Rorabaugh, Glenn E. Stout, and Chester O. Wisler. The Committee has been given full authority to organize the meeting, to co-opt the services of others, and to appoint such other committees as may be desirable.

The Sections of Meteorology, Oceanography, Volcanology, and Hydrology are tentatively planning to organize regionally in the Pacific Northwest. The Committee appointed for purposes of organization consists of Phil E. Church, Richard H. Fleming, Norbert H. Leupold, J. Hoover Mackin, and Harold G. Wilm. The Committee is to organize itself, to designate its own Chairman and Secretary, and to co-opt the services of others as may seem desirable. To facilitate the first meeting of the Committee, Richard H. Fleming has been designated as Chairman pro tem.

The Section of Hydrology has been investigating the South Rocky Mountain Area and the North Central Area to ascertain whether there is a desire on the part of the membership in those regions to organize the hydrologic interests.

Publications--We are still currently publishing an edition of 5,200 of our Transactions. The October 1951 issue is now in the hands of the printers. The August issue contained the papers of the colloquium on "Plastic flow and deformation within the Earth." An application has been made by IUGG to UNESCO for support in the publishing of this colloquium, the total cost of which was between $1,100 and $1,200. Action taken in Brussels supported an application for $500.

Student subscriptions totaling about 25 are now being sent out. We believe that the number will grow as word of this spreads through educational institutions.

The Index of the Transactions for the first 25 years, 1920-1944 inclusive, is about ready for the printers. Cards are being sent to members and subscribers in order that firm orders may be secured and a basis established for determining the size of the edition. The Editorial and Publication Committee has estimated that at least one thousand of the Index will be sold, and on this basis at a pre-publication price of $2.50. The Executive Committee two years ago set up a revolving fund of $1,000 to facilitate the compilation of this Index. Up to October 1, 1951 there has been a total expenditure of $670.37 from the fund.

Affiliation with the AAAS--In accordance with the instructions of the Executive Committee, affiliation with the AAAS has been completed. John Putnam Marble and Waldo E. Smith have been designated as our representatives on the Council, the first for a two-year term and the second for a one-year term.

News Items--The American Geophysical Union has been invited to send a representative to the Third National Conference of the U. S. National Commission for UNESCO to be held in New York January 27-31, 1952. Gordon G. Darkenwald of Hunter College has been designated by the President.

We were also invited to send a representative to the inauguration of the new Chancellor of the University of Chicago on October 18. Joseph C. Boyce, Associate Laboratory Director of the Argonne National Laboratory, was designated by the President.

An invitation has just been received to send a representative to the inauguration of the new President of the University of Arizona to be held November 16, 1951.

Antonio Marussi of the University of Trieste and of the Instituto Geografico Militare in Florence will give a set of eight lectures in a seminar course at Georgetown University beginning October 31, 1951. His topic will be the relation of differential geometry to geodesy. In addition, on November 13, 1951, he will give a colloquium under the auspices of the Department of Astronomy at Georgetown University.

We have continued to send exchange publications to the libraries of various bureaus, chiefly the Library of Congress and the Library of the Weather Bureau. Since our last meeting we have had acknowledgment of 451 items by the Library of Congress.

Berte R. Haigh of University Lands of the University of Texas has advised of the desire to establish a new seismological station in the El Paso area, and has written for aid and suggestions. The help requested has been forwarded and we are hopeful that AGU has thus aided in the establishment of one more seismological station.

Some months ago a request was received from the Administración General de Obras Sanitarias de la Nacion in Argentina for permission to reprint certain papers on hydrology that appeared in our Transactions, chiefly in the 1930's. Permission was granted with the understanding that similar permission would be obtained from the authors. One by former President O. E. Meinzer, and others by Theis and Fishel, were published in the first half of 1951.

Word has come in from the Society of Exploration Geophysicists that a West European Geophysical Union has been established as the West Europe Local Section of the Society. This is obviously to be an organization of exploratory geophysicists only.

Attention is called to the International Geological Congress to be held in Algeria, September 8 to 15, 1952. On the request of the Congress we have forwarded a copy of our Membership Directory, suggesting that those affiliated with the Sections of Seismology, Volcanology, and Tectonophysics will probably be especially interested, and also a good many affiliated with the Section of Hydrology who have a strong interest in ground-water hydrology.

Indiana University is considering the establishment of a training program in meteorology for the Air Force, and, in reply to a request, sources of information regarding persons who might be helpful in staffing this program were furnished.

Attention is called to an article in Occupational Trends entitled "New frontiers in meteorology" which appeared in the May-June issue. Encouragement of the publication of similar papers relating to other aspects of geophysics seems desirable.

Activities with Respect to National Research Council

Grant for 1952--A grant has been made by the National Research Council of $400 to aid the Union in carrying on its work as the Committee on Geophysics and as the American National Committee of the International Union of Geodesy and Geophysics for the fiscal year 1952.

Bibliography of Hydrology--The International Association of Hydrology is bringing the Bibliography of Hydrology of the various member countries up to date from the year 1940. To this end the Section of Hydrology made the recommendation that a contract be entered into with the principal interested federal agencies to compile the Bibliography. This contract was signed in the closing days of the fiscal year between the National Academy of Sciences on our behalf and the Bureau of Reclamation, representing a group of Federal agencies. It is anticipated that the Bibliography will be completed by June 30, 1952, and will cost about $11,000. Ray K. Linsley is doing most of the work of compilation. The office of the Union will edit the Bibliography and prepare the master copy, following which the master copy will be turned over to the Bureau for offset printing. Three hundred copies will be supplied without charge to the Union for the International Association of Hydrology. Copies will be available to individuals at a nominal charge.

Distribution of Publications of the International Union and its Associations--The publications of 1948 of the Association of Terrestrial Magnetism and Electricity and of the Association of Hydrology have been distributed in the United States. Two hundred copies of the former were received and 100 of the latter. The Executive Committee has ruled that this distribution shall be done by the office without cost to the AGU, and accordingly we have set up quite a firm mailing list of libraries and other organizations who are willing to defray the cost of handling and mailing. It is expected that the publications relating to Oceanography will be similarly mailed soon. One copy of the publications of the Association of Hydrology was sent to the Library of Congress without charge and a special letter of acknowledgment has been received.

In accordance with the action of the Executive Committee on May 2, 1951, a payment of $300 has been made to the International Association of Volcanology to clear our obligation for 300 copies of the 1939 publications of this Association; twenty copies of these publications have been received and are available to libraries upon payment of packing and postage charges.

Resolutions--The resolutions passed at the Thirty-Second Annual Meeting were transmitted appropriately as directed, for the most part over the signature of the Executive Secretary of the National Research Council, George D. Meid, Acting. A number of responses have come back through the Council indicating appreciation.

Distribution of Excess of Old Transactions--During the summer months about 150 partial sets of excess Transactions have been forwarded to foreign addresses through International Exchange. Most of these addresses were those on the mailing list of the various International Associations. From the responses that have been received, these sets, though partial, have been very welcome.

Review of Employment Opportunities for Earth Scientists--The Bureau of Labor Statistics of the Department of Labor is preparing a publication of employment opportunities for Earth scientists. A copy of this, sent to the American Geophysical Union for review, was extensively and constructively criticized by the Honorary President and the Executive Secretary. A revised draft has just recently come in for further review.

K. Hilding Beij, General Secretary

Action on the General Secretary's Report--The report was accepted.

International Matters

Walter H. Bucher, who attended the Ninth General Assembly of the International Union of Geodesy and Geophysics held in Brussels, Belgium, August 20 to September 1, 1951, as the Chief Delegate from the United States, reported on the Assembly. No attempt is made here to present his remarks in detail. Interested persons should consult the report in the October 1951 issue of the Transactions, pages 785-788, and other documents on file in the office of AGU. A few high points are mentioned. He commented that some in attendance suggested that the two-week meeting could be condensed into a single week. They represented those members of the Assembly who came unaware of, and unprepared for, the opportunities of broadening their own outlook over the whole field of geophysics and over possibilities of coordinated efforts which are the prime object for which the seven separate Associations are brought together. The special functions, especially the excursions, served this major purpose of giving men diverse chances of meeting and exchanging ideas. To bring about the dynamic impact of personalities upon each other and of new knowledge and ideas on men in other disciplines is the best reason for holding such meetings, and they cannot be hurried. Another difference lies between those who came without specific purpose and those who brought plans for joint enterprises and for the spreading of ideas. Few delegations came prepared, even with reference to changes in office. We were surprised to find that business meetings are conducted with little reference to our parliamentary procedure, and as a result difficult situations and dissatisfaction sometimes arose. It is important that we function as the National Committee from the United States, both with reference to the IUGG and to its constituent Associations. We should not let an annual meeting pass without attention to this phase. There are various projects that the Associations and their National Committees should work on, one worth while being the compilation of an international list of workers in the various fields such as has been compiled in terrestrial magnetism and electricity and in oceanography. The Section officers should keep in touch with the officers of the corresponding International Associations and important matters of the Associations should receive the attention of the corresponding National Committees (our Sections).

Comment was offered that information concerning the uses to which IUGG and its Associations spend their funds would be helpful in understanding the problems. It was also suggested that a Committee on International Cooperation might be formed for the purpose of giving special attention and emphasis to these problems.

Announcement was made that the Executive Board of the International Council of Scientific Union, of which IUGG is a member, was meeting in Washington, D. C., October 15-19, 1951.

Reports of Standing Committees

Statutes and By-Laws--Chairman McClain B. Smith reported that draft Statutes and By-Laws had been received from the South Pacific (California, Nevada, Hawaii, and probably Arizona) Regional Committee, that he and his Committee had gone over these, and while nothing was found to conflict with the Statutes and By-Laws of AGU, a number of recommendations were made. These he presented briefly. The Executive Committee approved that these suggestions be sent to the Regional Committee for their consideration. The suggestion was also made that the Committees concerned cooperate in working over these Statutes and By-Laws, and that when they are to be recommended for approval, they be sent to the Executive Committee in advance of the meeting.

Meetings--Chairman Marble noted the dates of coming meetings: Twenty-Seventh Regional Meeting in Pasadena, California, February 8-9, 1952; Thirty-Third Annual Meeting in Washington, D. C., May 5-7, 1952; and a meeting in Chicago, Illinois, September 11-12, 1952 in connection with the Centennial of Engineering. With regard to the Annual Meeting, he cited the tentative schedule that has been set up, and mentioned the tentative plan for a Symposium on the Interior of the Earth that he felt would be taking shape.

Editorial and Publication--Chairman Beij discussed the matter of the arrangement of papers in the Transactions and the objections to the present listing of papers by Sections into which compartments they frequently do not fit. There was discussion pro and con, but the decision was left to the Editorial and Publication Committee.

Budget--Chairman Eaton was absent, but on his behalf General Secretary Beij reported that

our printer had found it necessary to advance our printing rates, amounting to 20 to 25 per cent. It was voted that the budget for the Transactions be increased to meet the actual increase in printing cost.

Audit--Chairman Weightman reported that the financial statement for the year ending June 30, 1951 is in hand and would be audited soon. (The statement has since been audited and is found in Appendix 1.)

Reports of Sections

Volcanology--The matter of the renaming of the Section was referred to this meeting by action of the Executive Committee on May 2, 1951. After discussion, it was voted that no change be made in the name at present, but that petrologists, geochemists, and those interested in various aspects of radioactivity be encouraged to find an outlet and forum through this Section.

Hydrology--The matter of supporting the Committee on Fluid Permeation, Z59, of the American Standards Association was discussed. While the value of the work of the Committee was recognized and approved, it was felt that AGU cannot appropriate funds for such studies.

Affiliated Organizations

American Association for the Advancement of Science--John Putnam Marble outlined the new policy being discussed for adoption by AAAS [see Science, v. 114, no. 2966, pp. 471-472, Nov. 1951], shifting the emphasis from detailed aspects of the various branches of science to the problems of science as a whole, and to various unifying activities. Suggestions regarding this proposed policy are invited.

He advised that little interest was found in the membership in the Philadelphia area in holding an AGU meeting in connection with the coming meeting of AAAS in Philadelphia.

New and Unfinished Business

Third Polar Year--This matter was tabled at the meeting on May 2, 1951, awaiting action by the Ninth General Assembly of the IUGG in Brussels. At the Brussels meeting it was agreed that IUGG should aid in any plans for a Third Polar Year, but was unwilling to assume leadership in the endeavor. In the light of this action, it was agreed that AGU should take no further action at this time.

Adjournment--The meeting adjourned at 16h 30m.

K. Hilding Beij, General Secretary
Waldo E. Smith, Executive Secretary

APPENDIX 1--REPORT OF THE COMMITTEE ON AUDIT

Fiscal Year July 1, 1950 to June 30, 1951

R. H. Weightman, Chairman
A. G. McNish A. Nelson Sayre

The Committee on Audit has examined the books of the Union for the fiscal year ending June 30, 1951, and finds them in agreement with the statement of the Union's finances supplied by the General Secretary, which is attached hereto.

The cash assets of the Union at the beginning of the year amounted to $13,373.89, of which $12,085.08 was held as cash reserve, $1,180.91 in the Robert E. Horton Fund, and $107.90 in the Bowie Medal Fund. All three funds are carried in one account at the Riggs National Bank. The Permanent Fund, in reality our Invested Fund, amounted to $3,092.73 and consisted of $2,368 in Series F Bonds (maturity value $3,200) and $724.73 deposited in the Northwestern Federal Savings and Loan Association.

Receipts for the year from all sources totaled $38,343.96, while expenditures totaled $36,556.38, an increase in liquid funds of $1,787.58. It was found possible to increase the Permanent Fund by additions of $340 in cash and accumulated interest of $37.09 to the Northwestern Federal Savings and Loan Association account for a total of $1,101.82. The bond investment remained the same.

At the end of the year, the cash assets of the Union were $15,161.47, an increase of $1,787.58; $1,180.91 was held in the Horton Fund and $84.64 was held in the William Bowie Medal Fund, a decrease of $23.26. The Permanent Fund or Invested Fund was increased by $377.09 to $3,469.82.

We have again omitted the auxiliary statements, such as the list of outstanding checks at the end of the fiscal year. Such items have been checked, but we feel that there is no need for their publication.

Statement of assets and liabilities as of June 30, 1950

[From 1950 Report, see Trans., v. 31, p. 957, 1950]

Assets			
Cash Reserve	$12,085.08		
Robert E. Horton Fund	1,180.91		
William Bowie Medal Fund	107.90	$13,373.89	
Permanent Fund			
Series F bonds purchased prior to July 1, 1948 (maturity value $3,200) at cost	$ 2,368.00		
On deposit in Northwestern Federal Savings and Loan Association	724.73	3,092.73	
			$16,466.62
Bills receivable			7,499.61
			$23,966.23
Liabilities			
Bills payable			$ 540.93
Surplus (Capital Account)			23,425.30
			$23,966.23

Operating Statement

(Fiscal year ending June 30, 1951)

Receipts			
Grant			
National Research Council			$ 400.00
Income			
Dues 1948-1952 et seq			
1948	$ 100.00		
1949	165.00		
1950	3,571.00		
1951	24,987.89		
1952 et seq	154.00		
Corporation Memberships	700.00		
Life Memberships	200.00	$29,877.89	
Sales, Transactions		5,916.61	
Sales, Reprints		1,904.44	
Sales, Maps		16.00	
			37,714.94
Interest, Northwestern Federal Savings and Loan Association from January 1, 1950 to June 30, 1951			37.09
Miscellaneous contributions			191.93
			$38,343.96
Disbursements			
Publishing Transactions			
Printing		$ 7,853.84	
Preparing manuscript		7,017.02	
Mailing		742.17	$15,613.03
Reprints			1,597.39

General Expenses, Office of Union		
Salaries for services	$12,198.38	
Stationery and supplies	915.20	
Postage and communications	1,086.10	
Office equipment	307.72	$14,507.40
Expenses, meetings		
Annual Meeting	$ 763.05	
Regional Meetings	72.09	835.14
Expenses, Sections		
Meteorology	$ 7.00	
Terrestrial Magnetism and Electricity	5.44	
Hydrology	10.17	22.61
Expenses, Committees (Membership Committee)		689.23
Honoraria to editors		1,293.75
William Bowie Medal (paid from William Bowie Medal Fund)		23.26
Index of Transactions (first 25 years, 1920-1944), Salaries		77.19
Membership List		1,452.96
Miscellaneous		67.33
Investments: deposited in Northwestern Federal Savings and Loan Association as part of Permanent Fund ($270 plus check No. 3791 dated June 29, 1951 in favor of Association for $70; plus interest from Jan. 1, 1950 to June 30, 1951 of $37.09)		377.09
		$36,556.38

Excess of receipts over disbursements

Receipts	$38,343.96	
Disbursements	36,556.38	
Increase in liquid funds (Cash Reserve)		$ 1,787.58

Statement of assets and liabilities as of June 30, 1951

Assets			
Cash Reserve	$13,895.92		
Robert E. Horton Fund	1,180.91		
William Bowie Medal Fund	84.64	$15,161.47[a]	
Permanent Fund			
Series F bonds purchased prior to July 1, 1948 (maturity value $3,200) at cost	$ 2,368.00		
On deposit in Northwestern Federal Savings and Loan Association; $994.73 with accumulated interest of $37.09 and check for $70.00 not yet deposited on June 30, 1951	1,101.82	3,469.82	$18,631.20
Bills receivable			
Dues			
1951	$ 4,396.00		
1950 and 1951	3,994.00	$ 8,390.00	
Publications			
Transactions and miscellaneous	$ 196.28		
Reprints	196.74	393.02	8,783.02
			$27,414.22
Liabilities			
Bills payable and advance payments			
Dues in advance (including $154 received during 1951)		$ 230.00	
Subscriptions paid in advance		45.75	
Reprints paid in advance		58.50	
Miscellaneous advance payments		21.60	$ 355.85
Surplus (Capital Account)			27,058.37
			$27,414.22

[a]Riggs National Bank statement of June 29, 1951 $18,675.72
Less checks outstanding 3,514.25
Balance June 30, 1951 as above $15,161.47

BIBLIOGRAPHY

BIBLIOGRAPHY: GEODESY

BAESCHLIN, C. F., Die sphärische Berechnung von Streckennetzen, Soc. Helvétique Sci. Nat., Paul Attinger, Neuchatel, 49 pp., 1951.

BERGSTRAND, E., Measurement of distances with the geodimeter, Rikets Allmänna Kartverk. Medd. no. 16, 29 pp., 1951.

BERROTH, ALFRED, Direkte Messung der Laplaceschen Gleichung durch gleichzeitige Beobachtung von Azimutdifferenzen auf zwei Stationen, Veröffentlichung no. 1 - Reihe A: Höhere Geodäsie der Deutschen Geod. Komm., Bayerischen Akad. Wiss., pp. 5-26, 1951.

BERROTH, A., Die gravitationelle Deklination, ihre Bestimmung und ihre Elimination, Geof. Pura e Appl., Milano, v. 19, no. 3-4, pp. 2-8, 1951.

CLARK, J. S., and L. O. C. JOHNSON, Standardization of steel surveying tapes, Emp. Surv. Rev., v. 11, no. 81, pp. 118-128, 1951.

de GRAAFF-HUNTER, J., Earth curvature and refraction, Emp. Surv. Rev., v. 11, no. 81, pp. 132-138, 1951.

HIRVONEN, R. A., The motions of Moon and Sun at the solar eclipse of May 20, 1947, Veröff., Finn. Geod. Inst., Helsinki, no. 40, 35 pp., 1951. (This article is of interest in transoceanic connections of geodetic triangulation.)

JONES, L., Le levé gravimétrique de la Belgique (1947-1948), Inst. Géogr. Mil., Bruxelles, 64 pp., 2 pl., 1948.

JONES, L., Les anomalies isostatiques en Belgique, Inst. Géogr. Mil., Bruxelles, 8 pp., 3 pl., 1951.

KOBOLD, F., Die Bestimmung der Lotabweichungskomponenten im Meridian des St. Gotthard aus Höhenwinkelmessungen, Soc. Helvétique Sci. Nat., Paul Attinger, Neuchatel, 12 pp., 1 pl., 1951.

LEDERSTEGER, KARL, Numerische Untersuchungen über die Perioden der Polbewegung, Sonderheft 7, Österreich. Zs. für Vermessungswesen, Wien, 59 pp., 1949.

LEDERSTEGER, KARL, Der Anschluss des Ostseeringes an das europäische Lotabweichungssystem, Österreich. Zs. für Vermessungswesen, Wien, v. 37, no. 4-6, 17 pp., 1949.

LEDERSTEGER, KARL, Zur Analyse der Laplaceschen Widersprüche, Sonderheft 8, Österreich. Zs. für Vermessungswesen, Wien, 22 pp., 1949.

LEDERSTEGER, KARL, Die Näherungsmethoden des astronomischen Nivellements und das Geoid im Nordteil des Meridianbogens Grossenhain-Kremsmünster-Pola, Österreich. Zs. für Vermessungswesen, Wien, v. 39, no. 2-4, 20 pp., 1951.

LEDERSTEGER, KARL, Die Bestimmung des mittleren Erdellipsoides und der absoluten Lage der Landestriangulationen, Sonderheft 12, Österreich. Zs. für Vermessungswesen, Wien, 140 pp., 1951.

LOZANO CALVO, LUIS, Formule de la gravité normale en Espagne, Talleres Inst. Geogr. y Catastral, Madrid, 54 pp., 4 pl., 1951.

LOZANO CALVO, LUIS, Método para rectificar la red gravimétrica nacional y sus enlaces internacionales mediante observaciones con gravímetro, Rev. Geof., Madrid, v. 10, no. 38, pp. 73-84, 1951 (summary in English).

MADER, KARL, Das Newtonische Raumpotential prismatischer Körper u. seine Ableitungen bis zur dritten Ordnung, Sonderheft 11, Österreich. Zs. für Vermessungswesen, Wien, 74 pp., 1951.

MARCHANT, R., La généralisation de la méthode des moindres carrés par les procédés de l'algèbre matricielle, Inst. Géogr. Mil., Bruxelles, 57 pp., 1951.

MARUSSI, ANTONIO, Sulla rappresentazione del geoide sull'ellipsoide, Boll. Geod. e Sci. Affini, v. 10, no. 3, pp. 331-337, 1951 (summary in English).

MELCHIOR, P. J., A new method of analysis of the movement of the pole at the surface of the Earth, Bull. Acad. R. Belge Cl. Sci., v. 37, pp. 155-185, 1951 (in French) [abstr. in Phys. Abstr., v. 54, no. 644, p. 693, 1951].

MELCHIOR, P. J., and A. HUAUX, The annual displacement of the axis of rotation of the Earth with respect to the terrestrial globe, in relation to an annual oscillation of the instantaneous principal axis of inertia of the Earth, Bull. Acad. R. Belge Cl. Sci., v. 37, pp. 155-185, 1951 (in French) [abstr. in Phys. Abstr., v. 54, no. 644, p. 693, 1951].

MOROSINI, LUIGI, Rapport sur l'activité géographique militaire italien dans le domaine de la triangulation et du nivellement de précision pendant les trois années, 1948-1949-1950, presented at 9th Gen. Assembly, IUGG, Brussels, 1951, Boll. di Geod. e Sci. Affini, v. 10, no. 3, pp. 305-312, 1951.

MÜHLIG, F., The 24m interference comparator of the Potsdam Geodetic Institute, Deutsche Akad. Wiss., Berlin, Veröff. Geodät Inst., Potsdam, v. 2, 50 pp., 1949 (in German) [abstr. in Phys. Abstr., v. 54, no. 644, p. 693, 1951].

NADAL, I., and R. RAVINA, Medidas de intensidad de la gravedad en el mar, Urania, v. 36, no. 226, pp. 101-118, 1951.

REICHENEDER, K., Theory of errors and the adjustment of chains of diamond-shaped figures in radial triangulation, Deutsche Akad. Wiss. Berlin, Veröff. Geodät. Inst., Potsdam, no. 1, 98 pp., 1949 (in German) [abstr. in phys. Abstr., v. 54, no. 644, p. 694, 1951].

SALVIONI, GUIDO, Progetto della nuova rete altimetrica fondamentale (Livellazione di alta precisione), Boll. Geod. e Sci. Affini, v. 10, no. 3, pp. 319-330, 1951.

SILVA, GIOVANNI, Sulla caduta libera dei gravi, Boll. di Geod. e Sci. Affini, v. 10, no. 3, pp. 351-360, 1951 (summary in English).

SILVA, G., and G. BOAGA, Bibliografia Geodetica Italiana (1931-1940), R. Comm. Geod. Italiana, Bologna, 80 pp., 1942.

SZENT-IVÁNYI, G., L'instruction de Joseph le II, pur levers cadastraux, Földmérés. Közlem., v. 3, pp. 129-137, 1951 (in Hungarian with summary in French, p. 137).

TAKAHASI, R., K. HIRANO, and I. AITA, Results of precise levelings executed in the epicentral region of the Imaichi earthquake, Bull. Earthquake Res. Inst., Tokyo Univ., v. 28, no. 3-4, pp. 443-447, 1950 (in English).

TANNI, L., The geoidal undulations and disturbing masses, Isostatic Inst. Internat. Assn. Geod., Helsinki, Pub. 25, 19 pp., 1951

WHITE, GEORGE W., Lewis Evans' early American notice of isostasy, Science, v. 114, no. 2960, pp. 302-303, 1951.

WOLF, HELMUT, Beitrag zur Frage der persönlichen Gleichung bei astronomischen Azimuthbestimmungen, Boll. Geod. e Sci. Affini, v. 10, no. 3, pp. 361-377, 1951 (summary in English).

BIBLIOGRAPHY: SEISMOLOGY

AKIMA, T., Experiments on the overturnings of circular columns by the aid of a shaking table, Bull. Earthquake Res. Inst., Tokyo Univ., v. 28, no. 3-4, pp. 333-348, 1950.

ALFORD, J. L., G. W. HOUSNER, and R. R. MARTEL, Spectrum analyses of strong-motion earthquakes, Earthquake Res. Lab., Calif. Inst. of Tech., 110 pp., 1951.

ASADA, T., and Z. SUZUKI, On micro-earthquakes observed after the Imaichi earthquake, Dec. 26, 1949, Bull. Earthquake Res. Inst., Tokyo Univ., v. 28, no. 3-4, pp. 415-420, 1 pl., 1950.

BÅTH, MARKUS, The distribution of microseismic energy with special reference to Scandinavia, Arkiv för Geofys., v. 1, no. 13, pp. 359-393, 1951.

BÅTH, MARKUS, The microseismic importance of cold fronts in Scandinavia, Arkiv för Geofys., v. 1, no. 12, pp. 267-358, 1951.

BULLEN, K. E., Theoretical amplitudes of the seismic phase PKJKP, Mon. Notices, R. Astr. Soc., London, v. 6, no. 3, pp. 163-167, 1951.

CANTOS FIGUEROLA, J., Investigación sísmica en Baños de la Encina, Rev. Geofís., v. 10, no. 37, pp. 1-19, 2 pl., 1951.

EARTHQUAKE RESEARCH INSTITUTE, Observation of aftershocks carried out in the Imaichi District, Tochigi Prefecture, Tokyo Univ., Bulletin, v. 28, no. 3-4, pp. 387-392, 1 pl., 1950.

EARTHQUAKE RESEARCH INSTITUTE, Seismometrical data of the Imaichi earthquake, Dec. 26, 1949, Tokyo Univ., Bulletin, v. 28, no. 3-4, pp. 471-472, 5 pl., 1950.

FAUST, L. Y., Seismic velocity as a function of depth and geologic time, Geophysics, v. 16, pp. 192-206, 1951 [abstr. in Phys. Abstr., v. 54, no. 644, p. 760, 1951].

GEES, R., Nuevas investigaciones con el método sísmico de refracción, de masas salinas achatadas y escarpadas, en Alemania del Noroeste, Rev. de Geof., Madrid, v. 10, no. 38, pp. 85-97, 1951.

HAGIWARA, T., and K. KASAHARA, On aftershocks accompanying the Imaichi earthquake, Dec. 26, 1949, Bull. Earthquake Res. Inst., Tokyo Univ., v. 28, no. 3-4, pp. 393-400, 1 pl., 1950 (in English).

HAGIWARA, T., and T. RIKITAKE, Observation of the deformation of the Earth's surface in the vicinity of the epicentres of the Imaichi earthquake, Bull. Earthquake Res. Inst., Tokyo Univ., v. 28, no. 3-4, pp. 435-441, 1950 (in English).

HASKELL, NORMAN A., The dispersion of surface waves on multi-layered media, Geophys. Res. Papers no. 9, AF Cambridge Res. Center, 28 pp., 1951.

HEE, A., Catalogue des séismes algériens de 1850 à 1911, An. Inst. Phys. du Globe, Univ. Strasbourg, v. 6, pp. 41-49, 1950.

HOMMA, S., On the propagation of dispersive seismic waves, Geophys. Mag., Tokyo, v. 22, no. 3, pp. 209-236, 1951 [abstr. in Appl. Mech. Rev., v. 4, no. 9, p. 500, 1951].

HONDA, T., Land slip in the Imaichi district revealed from the breaks in the well tubes, Bull. Earthquake Res. Inst., Tokyo Univ., v. 28, no. 3-4, pp. 449-455, 1950 (in English).

KANAI, K., and T. SUZUKI, Experimental study of vibrations of structures caused by aftershocks of Imaichi earthquake of Dec. 26, 1949, Bull. Earthquake Res. Inst., Tokyo Univ., v. 28, no. 3-4, pp. 465-470, 1 pl., 1950.
KANAI, K., and T. TANAKA, On the damage to buildings by the Imaichi earthquake of Dec. 26, 1949, Bull. Earthquake Res. Inst., Tokyo Univ., v. 28, no. 3-4, pp. 461-464, 1950.
KAWASUMI, H., The Imaichi earthquake of December 26, 1949, general description, Bull. Earthquake Res. Inst., Tokyo Univ., v. 28, no. 3-4, pp. 355-367, 1950.
KISHINOUYE, F., Instrumental recording of a landslide caused by the Imaichi earthquake of Dec. 26, 1949, Bull. Earthquake Res. Inst., Tokyo Univ., v. 28, no. 3-4, pp. 457-459, 1 pl., 1950.
KOSHIKAWA, Y., Seismometrical study of the Imaichi earthquake on Dec. 26, 1949, Bull. Earthquake Res. Inst., Tokyo Univ., v. 28, no. 3-4, pp. 369-377, 1950.
MILNE, W. G., Bibliography of seismology no. 8, items 7418-7570, July to December, 1950, Pub. Dominion Obs., Ottawa, v. 14, pp. 167-185, 1951.
MIYAMURA, S., and T. AKIMA, Über die Beobachtung der Nachbeben des Imaichi-bebens am Dorfe Hunyu, Provinz Totigi, Bull. Earthquake Res. Inst., Tokyo Univ., v. 28, no. 3-4, pp. 421-433, 3 pl., 1950 (in Japanese with abstract in German).
MORIMOTO, R., Geology of Imaichi district with special reference to the earthquake of Dec. 26, 1949, Bull. Earthquake Res. Inst., Tokyo Univ., v. 28, no. 3-4, pp. 379-386, 2 pl., 1950.
NAKAMURA, SAEMON TARO, On visco-elastic medium (pt. 4), Sci. Reports, Tohôku Univ., v. 3, no. 1, pp. 48-52, 1951.
NASU, N., Vibration tests of defective buildings, Bull. Earthquake Res. Inst., Tokyo Univ., v. 28, no. 3-4, pp. 349-353, 1950 (in English).
OMOTE, S., Aftershocks of Imaichi earthquake observed at Nishi-oashi Station, Bull. Earthquake Res. Inst., Tokyo Univ., v. 28, no. 3-4, pp. 401-413, 2 pl., 1950.
OMOTE, S., On the coda waves of earthquake motions, pt. 5, Bull. Earthquake Res. Inst., Tokyo Univ., v. 28, no. 3-4, pp. 285-309, 1950.
OMOTE, S., On the aftershocks of the Fukui earthquake, pt. 2, Bull. Earthquake Res. Inst., Tokyo Univ., v. 28, no. 3-4, pp. 311-319, 1950.
PETERSCHMITT, E., Étude de la magnitude des seismes, An. Inst. Phys. du Globe, Univ. Strasbourg, v. 6, pp. 51-58, 1950.
ROTHE, J. P., Les séismes de Kerrata (1949) et la séismicité de l'Algérie, An. Inst. Phys. du Globe, Univ. Strasbourg, v. 6, pp. 3-40, 1950.
SATÔ, Y., Transformation of wave-functions related to the transformation of coordinate systems, II, Bull. Earthquake Res. Inst., Tokyo Univ., v. 28, no. 3-4, pp. 175-217, 1950.
STOKER, J. J., Nonlinear vibrations in mechanical and electrical systems, 292 pp., Interscience Pub., New York, 1950 [rev. by H. T. H. Piaggio in Nature, v. 168, p. 49, 1951].
STONELEY, R., Polarisation of the S-phase of seismograms, An. Geofis., v. 4, pp. 3-8, 1951 [abstr. in Phys. Abstr., v. 54, no. 644, p. 760, 1951].

BIBLIOGRAPHY: METEOROLOGY

ARAKAWA, H., Analysis of the tropopause and the stratospheric field of temperature of a mature typhoon, Papers in Met. and Geophys., Met. Res. Inst., Tokyo, v. 2, no. 1, pp. 1-5, 1951.
ARAKAWA, H., Bernoullian surface in meteorology, Papers in Met. and Geophys., Met. Res. Inst., Tokyo, v. 2, no. 1, pp. 65-66, 1951.
ARAKAWA, H., and K. TSUTSUMI, Interdiurnal temperature variabilities and temperature singularities in Japan, Papers in Met. and Geophys., Met. Res. Inst., Tokyo, v. 2, no. 1, pp. 40-44, 1951.
aufm KAMPE, H. J., Das Wetter und seine Ursachen, Verlag Dietrich Steinkopff, Darmstadt, 164 pp., 1951.
BLOOMFIELD, J. J., Health implications of air pollution, Proc. Air Pollution Smoke Prevention Assn. Amer., pp. 76-81, 1950 [abstr. in Chem. Abstr., v. 45, no. 14, p. 6329e, 1951].
BUSCHNER, WERNER, Untersuchungen über Verlagerung, Aufbau und Dynamik zweier winterlicher Kaltlufttropen, Ber. Deuts. Wetterdienst, US-Zone, nr. 23, Bad Kissingen, 30 pp., 1951.
DOPORTO, M., Theory and description of a gradient wind computer, Met. Serv. Geophys. Pub., Dublin, v. 3, no. 1, 8 pp., 1950 [abstr. in Appl. Mech. Rev., v. 4, no. 8, p. 484, 1951].
FAUST, H., Kaltfronten und Gewitter: (A) Über Kaltfronten und ihre Eintellung; (B) Über Entstehung und Energiequelle der Gewitterböen; (C) Statistische Untersuchungen an Gewittern im frontfreien Raum, Ber. Deuts. Wetterdienst, US-Zone, no. 24, Bad Kissingen, 55 pp., 1951.
FORSGREN, SVEN K. H., and OLOF F. PERERS, Vertical recording of rain by radar, Rep. Res. Lab. of Electronics no. 20, Trans. Chalmers Univ. of Tech. no. 107, 19 pp., 1951.
GEORGII-MENDOZA, WALTER, Beitrag zur Aerologie Argentiniens, Ber. Deuts. Wetterdienst, US-Zone, Bad Kissingen, no. 27, 18 pp., 1951.
GHERZI, E., The humidity of Macau, no. 1, pp. 9-15; Drawing weather maps and forecasting, no. 2, pp. 25-30, Obs. Met., Macau, 1951.

HATAKEYAMA, H., and K. UCHIKAWA, On the disturbance of the atmospheric potential gradient caused by the eruption smoke of the Volcano Aso, Papers in Met. and Geophys., Met. Res. Inst., Tokyo, v. 2, no. 1, pp. 85-89, 1951.

HERATH, FRIEDRICH, Studie über interdiurne Temperaturänderungen in der freien Atmosphäre über Mitteleuropa nach Registrierballonaufstiegen in Lindenberg und München, Ber. Deuts. Wetterdienst, US-Zone, nr. 25, Bad Kissingen, 14 pp., 1951 (with summary in English).

HOLLMANN, G., Fronts and development phases of a shifting cyclone in attached system of coordinates, Z. Meteor., v. 4, no. 1-2, pp. 39-47, 1950 (in German) [abstr. in Appl. Mech. Rev., v. 4, no. 8, p. 484, 1951].

ITOO, K., Phenomena of ice crystals in the air (On small ice crystals), Papers in Met. and Geophys., Met. Res. Inst., Tokyo, v. 2, no. 1, pp. 67-75, 1951.

KAMIYAMA, K., T. SUZUKI, and M. KAWAMORI, A survey on the dwelling conditions of community houses from the climatological point of view, Papers in Met. and Geophys., Met. Res. Inst., Tokyo, v. 2, no. 1, pp. 90-94, 1951.

KORHONEN, V. V., Die mittlere Niederschlagshöhe in Finnland in den Jahren 1886-1935, Mitt. Met. Zentralanstalt, Helsinki, no. 34, 13 pp., 14 pl., 1951.

MALET, L., Précision des sondages aérologiques, Mém. Inst. R. Mét. Belgique, v. 46, 23 pp., 8 pl., 1951.

MEINHOLD, H., Die Peilung atmosphärischer Störungen zum Zwecke der Wetterprognose, Ber. Deuts. Wetterdienst, US-Zone, Bad Kissingen, no. 26, pp. 1-8, 1951.

MORÁN, F., Una determinación inmediata de la onda de Airy del arco iris, Rev. Geofís., v. 10, no. 37, pp. 20-23, 1951.

NAKAMURA, SAEMON TARO, Meteorological statistics (pt. 2), Secular change in the air temperature, Sci. Rep., Tohôku Univ., v. 3, no. 1, pp. 13-22, 1951.

NAITO, K., On a method of preventing the ground-reflected wave effect in Rawin observation, Papers in Met. and Geophys., Met. Res. Inst., Tokyo, v. 2, no. 1, pp. 76-84, 1951.

NANNICHI, T., On the fluctuation of the Kurosiwo and Oyasiwo, Papers in Met. and Geophys., Met. Res. Inst., Tokyo, v. 2, no. 1, pp. 102-111, 1951.

OOSAWA, K., A normal broad-weather cycle in the "Baiu," the rainy season in Japan, Papers in Met. and Geophys., Met. Res. Inst., Tokyo, v. 2, no. 1, pp. 45-51, 1951.

ORGANISATION METEOROLOGIQUE INTERNATIONALE, Comparaison mondiale des radiosondes, Sous-commission mixte d'aérologie expérimentale, Sous-commission pour la comparaison des radiosondes, v. 1, 293 pp., v. 2, 45 pp., 1951.

PITA, PIO, Instrumentos meteorológicos, Su crítica y orientación moderna, Rev. Geofís., v. 10, no. 37, pp. 24-56, 1951.

POLLI, SILVIO, Andamento climatico stagionale e attività solare, Riv. Ecologia, v. 1, no. 5-6, pp. 300-308, 1950 (summaries in English and German).

SATO, T., On the equations of stationary motion, Papers in Met. and Geophys., Met. Res. Inst., Tokyo, v. 2, no. 1, pp. 52-57, 1951.

SATO, TAKAO, Über die Dämmerungserscheinungen auf der Erde überhaupt, Sci. Reports, Tohôku Univ., v. 3, no. 1, pp. 1-12, 1951.

SCHINDELHAUER, F., and H. ISRAËL, Die Peilung von Luftstörungen der drahtlosen Telegraphie zum Zwecke der Wettererkundung, Ber. Deuts. Wetterdienst, US-Zone, Bad Kissingen, no. 26, pp. 9-39, 1951.

SCHWERDTFEGER, WERNER, La depresión térmica del NW argentino, An. Soc. Cient. Argentina, v. 151, pp. 255-275, 1951 (summary in English).

SWINBANK, W. C., A sensitive vapor pressure recorder, J. Sci. Instr., v. 28, pp. 86-89, 1951 [abstr. in Phys. Abstr., v. 54, no. 641, p. 457, 1951].

TAKAHASHI, K., and Others, Studies on the seasonal weather forecasting (1st report), Papers in Met. and Geophys., Met. Res. Inst., Tokyo, v. 2, no. 1, pp. 6-29, 1951.

TAKEUCHI, M., Notes on the influence of motion on the temperature lapse rate and on the stability of dry and moist air, Papers in Met. and Geophys., Met. Res. Inst., Tokyo, v. 2, no. 1, pp. 58-64, 1951.

TAKEUCHI, M., On the influence of mountain ranges on cold front and masked phenomena of cold air masses, Papers in Met. and Geophys., Met. Res. Inst., Tokyo, v. 2, no. 1, pp. 30-39, 1951.

WIEGHARDT, K., On the propagation phenomena in the ground wind, Met. Rundsch., v. 2, no. 7-8, pp. 196-198, 1949 (in German) [abstr. in Appl. Mech. Rev., v. 4, no. 8, p. 484, 1951].

YAMAMOTO, GIICHI, and AKIRA MIURA, Opacity at Sendai, Sci. Rep., Tohoku Univ., v. 3, no. 1, pp. 23-33, 1951.

YAMAMOTO, GIICHI, and AKIRA MIURA, Saturation vapor pressure and size of condensation nucleus, Sci. Rep., Tohôku Univ., v. 3, no. 1, pp. 34-39, 1951.

BIBLIOGRAPHY: TERRESTRIAL MAGNETISM AND ELECTRICITY

ALFANO, L., Studi sulla interpretazione dei sondaggi elettrici verticali, Riv. Geof. Appl., v. 12, no. 1, pp. 21-35, 1951 (summary in English).

BATES, D. R., and M. NICOLET, Theory of the spectral emission from the molecule OH in the night-sky spectrum, C.-R. Acad. Sci., Paris, v. 230, pp. 1943-1945 , 1950 (in French) [abstr. in Phys. Abstr., v. 53, no. 634, p. 875, 1950].

BECKER, W., and W. DIEMINGER, The effective, noon recombination-coefficient of the F_2 layer deduced from critical frequency measurements during the Mögel-Dellinger effect on Nov. 19, 1949, Zs. Naturforsch., v. 5a, pp. 308-311, 1950 (in German) [abstr. in Phys. Abstr., v. 53, no. 635, p. 928, 1950].

BERLAGE, H. P., The fundamental relation between the magnetic moment and the structure of rotating celestial bodies, Nature, v. 165, pp. 242-243, 1950. (Said to be a modification of Angenheister's theory, free from the latter's apparent quantitative defects.)

COLOQUE INTERNATIONAL TENU À LYON EN 1947, Relations entre les phenomenes solaires et geophysiques, Editions Rev. optique théorique et instrumentale, Paris, 312 pp., 1949 [rev. in Nature, v. 167, p. 745, 1951]. (Contains 43 memoirs, by Vegard, Dufay, Bernard, Chapman, Thellier, Mitra, Menzel, Alfven, and others.)

CUBILLO FLUITERS, JOSÉ, Carta nacional de declinaciones magnéticas--Hoja especial del Territorio Peninsular, 2 v., Inst. Geog. Catastral, Madrid, 1950. (Includes a general introduction to geomagnetism, with 267 pages of text and 149 illustrations.)

CURRIE, B. W., Auroral research in Canada, in Physics in Canada 1950 (pub. Canadian Assn. Physicists) [abstr. in Canad. Geophys. Bull., v. 4, no. 3, p. 33, 1951].

CURRIE, B. W., J. H. MEEK, and P. M. MILLMAN, Bibliography of atmospheric ionization, Canad. Geophys. Bull., v. 4, no. 2, pp. 1-10, 1950. (Contains 134 entries pertaining to Canadian data or research, segregated in four categories.)

de MAGNEE, IVAN, The geoelectric delineation of the first pipe of kimberlite in the diamond fields of Kasai (Belgian Congo), Internat. Geol. Cong., Grt. Brt., 18th Sess., 1948, Rep., pt. 5, Proc. Sec. D, pp. 52-58, 1950 (in French) [abstr. in Geophys. Abstr., p. 94, 1951].

de MIGUEL y GONZALEZ-MIRANDA, LUIS, Corrientes teluricas año 1948, Obs. Cent. Geofis., Toledo, 40 pp., Madrid, 1951; also año 1949, 64 pp., Madrid, 1951.

de YRIZAR, PEDRO, and Others, Estudio sobre equipos magnéticos para determinación de valores absolutos, 116 pp., Inst. Geográfico y Catastral, Madrid, 1950.

DIGIESI, DOMENICO, The new magnetic chart of the Istituto Geografico Militare with isogonals for 1948, Boll. Geod., no. 4, pp. 193-194, 1949 (in Italian) [abstr. in Geophys. Abstr., p. 63, 1951].

EWEN, H. I., and E. M. PURCELL, Radiation from galactic hydrogen at 1420 mc/s, Nature, v. 168, p. 356, 1951.

FERRELL, O. P., Enhanced trans-equatorial propagation following geomagnetic storms, letter in Nature, London, v. 167, pp. 811-812, 1951 [abstr. in Phys. Abstr., v. 54, no. 645, p. 859, 1951].

FRIEDMAN, BERNARD, Propagation in a nonhomogeneous atmosphere, Comm. Pure and App. Math., v. 4, pp. 317-350, 1951. (Presented at June 1950 Symposium on the theory of electromagnetic waves. Other papers given at this Symposium and published in same issue are by M. KLINE, N. MARCUVITZ, and S. O. RICE.)

GERSON, N. C. (Ed.), Proceedings of the colloquium on mesospheric physics, Geophys. Res. Papers no. 8, AF Cambridge Res. Center, 100 pp., 1951.

GILCHRIST, L., A. R. CLARK, and B. BERNHOLTZ, Methods of determination of the average resistivity of a two-layered medium, Canad. Mining J., pp. 3-12, Jan. 1950 [abstr. in Canad. Geophys. Bull., v. 4, no. 1, p. 16, 1950].

GILCHRIST, L., N. ROSTOKEN, and B. BERNHOLTZ, Distribution of potential in a two-layered medium due to an internal source and sink, and the determination of the approximate average resistivity of the medium, Canad. J. Res. (Sec. A), v. 28A, pp. 1-28, 1950 [abstr. in Canad. Geophys. Bull., v. 4, no. 1, p. 17, 1950].

GODARD, L., Etude sur les propriétés magnétiques des coulées de lave; application à la détermination des thalwegs souterrains, An. Inst. Phys. Globe, Univ. Strasbourg, v. 6, pp. 59-69, 1950.

GRANT, C. K., Magnetic surveys in the Middleback Range, South Australia Dept. Mines, Mining Rev., no. 90, pp. 163-169, 1950 [abstr. in Geophys. Abstr., p. 88, 1951].

HAALCK, H., New views on the origin of the magnetic field of the solid Earth, Geofis. Pura e Appl., v. 18, pp. 132-142, 1950 (in German) [abstr. in Geophys. Abstr., p. 61, 1951].

HAGIHARA, Y. (ed.), Provisional reports of observations of the partial eclipse of the Sun on Sept. 12, 1950, Sci. Council Japan, 85 pp., 1951. (Comprises 21 reports dealing with geomagnetism, solar noise, ionospheric variations, and cosmic rays.)

HAYNES, S. K., and J. W. WEDDING, The use of three long rectangular coils for neutralization of the Earth's magnetic field in a lens-type beta-ray spectrometer, Rev. Sci. Inst., v. 22, pp. 97-101, 1951. (Resembles in some respects the arrangements investigated by F. K. HARRIS, U. S. Nat. Bur. Stds. J. Res., v. 13, pp. 391-410, 1934.)

HEAVISIDE, OLIVER, Electromagnetic theory, 416 pp., Dover Pub., Inc., New York, 1950 [rev. by W. Jackson in Nature, v. 168, p. 136, 1951]. (Reprint of three volumes in one, with critical and historical introduction by Ernst Weber.)

HOGE, EDMOND, Reflections on the distribution of the Earth's magnetism in Belgium, An. Soc. Sci. Bruxelles, v. 65, pp. 71-78, 1951 (in French) [abstr. in Geophys. Abstr., p. 63, 1951].

KAKIOKA MAGNETIC OBSERVATORY, Geomagnetic indices, K and C, at Kakioka, 1932, 1933, and 1942-1950, Mem. Kakioka Mag. Obsy., v. 6, pp. 69-92, 1951.

KLINKENBERG, L. J., Analogy between diffusion and electrical conductivity in porous rocks, Geol. Soc. Amer. Bull., v. 62, pp. 559-564, 1951 [abstr. in Geophys. Abstr., p. 92, 1951].

KOENIGSFELD, L., and PH. PIRAUX, Un nouvel électromètre portatif pour la mesure des charges électrostatiques par système électronique, Mém. Inst. R. Mét. Belgique, v. 45, 21 pp., 4 pl., 1951.

KUMAGAI, N., N. KAWAI, and T. NAGATA, Recent progress in paleomagnetism in Japan, J. Geomag. Geoelectr., v. 2, no. 3, pp. 61-65, 1950 [abstr. in Geophys. Abstr., p. 64, 1951].

MAPLE, E., W. A. BOWEN, JR., and S. F. SINGER, Evidence for ionosphere currents from rocket experiments near the geomagnetic equator, Letter in Phys. Rev., v. 82, pp. 957-958, 1951 [abstr. in Phys. Abstr., v. 54, no. 645, p. 858, 1951].

MEEK, J. H., Occurrence of E-region sporadic ionization through the auroral zone, Radio Propag. Lab., Defence Res. Board, Canada, Rep. 3, Jan. 1950 [abstr. in Canad. Geophys. Bull., v. 4, no. 1, p. 22, 1950].

MEINEL, A. B., The spectrum of the airglow and the aurora, Rep. Phys. Soc. Progr. Phys., v. 14, pp. 121-146, 1951 [abstr. in Phys. Abstr., v. 54, no. 645, p. 861, 1951].

MOROSINI, LUIGI, Rapport sur l'activité de l'institut géographique militaire italien, pour le magnetisme terrestre pendant les vingt dernieres années, presented at 9th Gen. Assembly, IUGG, Brussels, 1951, Boll. Geod. Sci. Affini, v. 10, no. 3, pp. 313-318, 1951.

NORINDER, H., and O. SALKA, The properties of artificial lightning discharges against a geologically heterogeneous surface, Conf. Int. Gr. Res. Elect. (CIGRE) Paper, no. 313, 19 pp., 1950 [abstr. in Phys. Abstr., v. 53, no. 634, p. 876, 1950].

PICKLE, C. B., Atlas of ionosphere records with interpretations and instructions on scaling, Nat. Bur. Stds. Rep. no. 1106, 14 pp., 78 pl., 1951.

PRICE, A. T., Electromagnetic induction in a semi-infinite conductor with a plane boundary, Q. J. Appl. Math., v. 3, pp. 385-410, 1950 [rev. by A. Erdélyi in Math. Tables and Aids to Comp., v. 5, pp. 159-160, 1951].

PUERTAS, C. GAIBAR, La variación secular de la intensidad geomagnética y su influjo en la distribución geográfica de la imantación terrestre, Urania, v. 36, no. 226, pp. 65-95, 1951.

RIKITAKE, T., Electromagnetic induction within the Earth and its relation to the electrical state of the Earth's interior, pt. 1 (2) and pt. 2, Bull. Earthquake Res. Inst., Tokyo Univ., v. 28, pp. 219-262 and 263-283, 1950. (For reference to pt. 1 (1) see these Trans., v. 32, p. 478, 1951.)

ROMAÑÁ, ANTONIO, Sobre el carácter general de la clasificación de las bahias geomagnéticas y su ley de aparición durante el día, Pub. Observ. del Ebro, Misc. no. 7, Geofis. Pura Appl., v. 18, 8 pp., 1950 (summaries in French and English).

ROUCH, J., Observations of the atmospheric-electric field at Monaco, C.-R. Acad. Sci., Paris, v. 230, pp. 1485-1487 (in French), 1950 [abstr. in Phys. Abstr., v. 53, no. 634, p. 876, 1950].

SCHNEIDER, OTTO, and MARIA ELENA SALUZZI, Efecto de curvatura en la perturbación residual del geomagnetismo, Meteoros, v. 1, no. 2-3, pp. 125-133, 1951 (summary in English).

SCHUMANN, W., On the introduction and importance of an iron-index for minerals, Gerlands Beitr. Geophysik, v. 61, pp. 70-78, 1949 [abstr. in Geophys. Abstr., p. 87, 1951].

SIVARAMAKRISHNAN, M. V., Some geomagnetic disturbances at Alibag Observatory (India) and allied radio and solar effects (1937-46), Indian J. Met. Geophys., v. 1, pp. 207-219, 1950 [abstr. in Geophys. Abstr., p. 62, 1951].

SPECCHIA, O., and M. ADDARIO, Microbalance for measuring the susceptibility of solid bodies, Ist. Lombardo Rev., v. 77, pp. 620-626, 1944 [abstr. in Geophys. Abstr., p. 87, 1951].

SUNDE, E. D., Earth conduction effects in transmission systems, 373 pp., D. Van Nostrand Co., New York, 1949 [rev. in Geophys. Abstr., p. 92, 1951].

WALDMEIER, M., Die Sonnenaktivität im Jahre 1949, Vierteljahrsschrift der Naturforschenden Gesellschaft, Zurich, v. 95, pp. 212-224, 1950 (summary in English).

WALDMEIER, M., Heliographische Karten der Photosphäre für das Jahr 1949, Pub. Eidg. Sternwarte, Zürich, v. 9, no. 4, pp. 87-113, 1950.

WELLS, H. W., Rapid changes in the ionosphere, Internat. Assn. Terr. Mag. Elec., Bull. 13, pp. 369-370, 1950 [abstr. in Phys. Abstr., v. 54, p. 684, 1951].

YOKOUCHI, Y., On the storms of earth-current potentials observed at Kakioka, Mem. Kakioka Mag. Obsy., v. 6, pp. 42-53, 1951 (in Japanese, with English summary).

BIBLIOGRAPHY: OCEANOGRAPHY

In this issue, recent Russian works in the field are continued from pp. 132-133 of the Transactions for February 1951.

ALEKIN, OLEG A., Obshchaia gidrokhimiia; khimiia prirodnykh vod (General hydrochemistry; chemistry of natural waters), Gidromet. izdvo, Leningrad, 206 pp., 1948.
DOBROLONSKIY, S. V., and V. A, TYUMENEVA, The use of oil for calming heavy seas, Izvest. Akad. Nauk, Ser. Geogr. Geofiz., v. 14, pp. 425-440, 1950.
IVANOV, K. I., Coefficient of light attenuation as a function of the diameters of particles suspended in water, Dok. Akad. Nauk, v. 74, pp. 925-929, 1950.
KORNEVA, L. A., Anomalous geomagnetic field and its equivalent in a system of currents in the world ocean, Dok. Akad. Nauk, v. 76, pp. 49-52, 1951.
KROTOV, B. P., Concerning genesis of submarine manganese deposits, Dok. Akad. Nauk, v. 77, pp. 93-95, 1951.
LEONOV, A. K., Water masses of the Sea of Japan, Met. Gidrol., no. 6, pp. 61-79, 1948.
LONGINOV, V. V., Reshaping of beaches on the North Caucasian Coast as a result of the August 1949 storm, Priroda, no. 7, p. 55, 1950.
LONGINOV, V. V , Role of compensatory currents near the bottom in moving materials on a bottom slope, Izvest. Akad. Nauk, Ser. Geog. Geofiz., v. 15, no. 2, pp. 75-80, 1951.
PANOV, D. G., Submarine landscapes of the world ocean, Izvest. Vses. Geogr. Obshch., v. 82, pp. 582-607, 1950.
SEKERZH-ZEN'KOVICH, Y. I., Theory of standing waves of finite amplitude on the surface of a heavy liquid of finite depth, Izvest. Akad. Nauk, Ser. Geogr. Geofiz., v. 15, no. 1, pp. 57-73, 1951.
SHISHKO, A. F., New calculation of elements in the heat balance of the White Sea, Met. Gidrol., no. 5, pp. 67-75, 1948.
SHULIEKIN, V. V., Terrestrial magnetic field and world ocean, Dok. Akad. Nauk, v. 76, pp. 57-60, 1951.
SKORNYAKOV, V. M., Problem of on-driven and off-driven changes of level and of seiches in the Baltic, Met. Gidrol., no. 2, pp. 67-70, 1948.
SRETENSKII, L. N., The refraction and reflection of plane waves in a liquid at a transition from one depth to another, Izvest. Akad. Nauk, Odtel. Tekh. Nauk, no. 11, pp. 1601-1614, 1950.
SRETENSKII, L. N., Waves generated by an underwater source below the surface of a sphere, Izvest. Akad. Nauk, Ser. Geogr. Geofiz., v. 13, pp. 473-496, 1949 [abstr. in Appl. Mech. Rev., v. 4, no. 2, p. 84, 1951].
TARTAKOVSKII, B. D., Sound transmitting layers, Dok. Akad. Nauk, v. 75, pp. 29-32, 1950.
TIMOFEEVA, V. A., Distribution of luminosity in a violently agitated medium, Dok. Akad. Nauk, v. 76, pp. 677-680, 1951.
TIMOFEEVA, V. A., The problem of the distribution of luminosity in the sea, Dok. Akad. Nauk, v. 76, pp. 831-834, 1951.
VELICHKINA, T. S., and I. L. FABELINSKII, A method of measuring the velocity of propagation of ultrasonic waves in fluids, Dok. Akad. Nauk, v. 75, pp. 177-180, 1950.
VELIKANOV, M. A., Discrete concept of turbidity, Dok. Akad. Nauk, v. 77, pp. 603-606, 1951.
VERSHINSKIY, N. V., Recording of fluctuations in the velocity vector of fluids, Dok. Akad. Nauk, v. 73, pp. 941-943, 1950.
VLADIMIROV, A. T., Formation of scalloped shorelines, Priroda, no. 7, p. 54, 1950.
YAMPOL'SKIY, A. D., Convection currents provided by thermal processes in the sea, Met. Gidrol., no. 5, pp. 63-66, 1948.
ZENKOVICH, V. P., The formation of lagoons, Dok. Akad. Nauk, v. 75, pp. 527-530, 1950.
ZENKOVICH, B. P., and V. I. BUDANOV, Deformation of a trochoidal wave at the shore, Met. Gidrol., no. 6, pp. 99-101, 1948.
ZHDANOV, A. M , Determination of the power equivalent of wave motion on seashore, Izvest. Akad. Nauk, Ser. Geogr. Geofiz., v. 15, no. 1, pp. 51-56, 1951.
ZHDANOV, A. M., Determination of flow power in shore deposits by direct observations, Izvest. Akad. Nauk, Ser. Geogr. Geofiz., v. 15, no. 2, pp. 81-90, 1951.
ZUBOV, N. N., L'dy Arktiki (Ice of the Arctic), Glavsevmorput, 359 pp., Moscow, 1945.

BIBLIOGRAPHY: VOLCANOLOGY

ALVIR, A. D., Is the Paracale granite or granodiorite of Tertiary Age? Some fundamental objections, Philippine Geologist (J. of the Soc.), v. 4, no. 3, pp. 24-34, 1950.
ARRIBAS, ALFREDO SAN MIGUEL, Ideas modernas sobre la petrogénesis de las rocas eruptivo-metamórficas y volcánicas, Notas Comunicaciones Inst. Geol. y Min., España, no. 22, p. 5, 1951.

AUDEN, JOHN B., Dykes in western India, a discussion of their relationships with the Deccan Traps, Trans. Nat. Inst. Sci. of India, v. 3, no. 3, pp. 123-157, 1949.

AUROUZE, JEAN, Étude géologique des feuilles Marotandrano-Manavara, Haut Commissariat, Madagascar, Bur. Géol. Générale, Service des Mines, Tananarive, Madagascar, Travaux 21, 50 pp., 1951.

BURRI, CONRAD, and PAUL NIGGLI, Die jungen Eruptivgesteine des Mediterranen Orogens, zweiter Haupteil: der Chemismus der postophiolithischen Eruptivgesteine, Sitz-Mineralogisch-Petrographisches Inst. Eidg., Tech. Hochschule, Zurich, Vulkaninstitut Immanuel Friedlaender, 206 pp., 1949.

CROCE, ROMEO, Algunas observaciones sobre los afloramientos graniticos, de rocas volcánicas antiguas y filónicas en gastre, Chubut, Rev. Buenos Aires Inst. Nac. Investigacion Cien. Nat., Cien. Geol., v. 1, no. 3, pp. 91-115, 1950.

de ANDRADE, N. M., and J. BRAK-LAMY, Um granito aurifero do Lépe (Angola), Bol. Museu Lab. Min. Geol., Fac. Ciên. Univ. Lisboa, no. 18, ser. 6a, pp. 51-60, 1950.

de ASSUNÇÃO, C. F. T., and J. BRAK-LAMY, Sobre os granitos de Pousa (Barcelos) e do Monte das Caldas, Bol. Museo Lab. Min. Geol., Fac. Ciên. Univ. Lisboa, no. 18, ser. 6a, pp. 61-67, 1950.

de ASSUNÇÃO, C. F. T., and J. BRAK-LAMY, Notas sobre a petrografia eruptiva do distrito de Beja, Bol. Museo Lab. Min. Geol., Fac. Ciên. Lisboa, no. 18, ser. 6a, pp. 81-95, 1950.

DORMOIS, ROBERT, Étude géologique des feuilles Andavakoera et Vohémar, Haut Commissariat, Madagascar, Bur. de Géol. Générale, Service des Mines, Tananarive, Madagascar, Travaux 12, 2nd ed. complete, 49 pp., 1950.

EFREMOV, N., To the problem of the genesis of the ferro-meteorites in connection with Lewis's hypothesis, Ukranian Tech. Univ. Sci. Rep., v. 15-17, pp. 64-71, 1950.

FINCH, R. H., and GORDON A. MacDONALD, Report of the Hawaiian Volcano Observatory for 1948 and 1949, U. S. Geol. Surv. Bull. 974-D, Contr. Gen. Geol., 1950, pp. 103-133, 1951.

FISCHER, G., Granit und Sial, Geol. Rundschau, v. 39, no. 1, pp. 32-77, 1951.

GUIGUES, J., Étude géologique des feuilles Anosibe Vatomandry, Haut Commissariat, Madagascar, Bur. Géol. Générale, Service des Mines, Tananarive, Madagascar, Travaux 13, 111 pp., 1950.

GUIGUES, JEAN, Étude géologique des feuilles Ramartina-Mandoto, Haut Commissariat, Madagascar, Bur. Géol. Générale, Service des Mines, Tananarive, Madagascar, Travaux 19, 93 pp., 1951.

GUYONNAUD, GEORGES, Étude géologique de la feuille Maevatanana, Haut Commissariat, Madagascar, Bur. Géol. Générale, Service des Mines, Tananarive, Madagascar, Travaux 24, 54 pp., 1951.

IMBO, G., and L. CASTERANO, Relazione su osservazioni effettuate in occasione di una nuova discesa sul fondo del cratere Vesuviano., Boll. Soc. dei Naturalisti in Napoli, v. 59, pp. 96-100, 1950 (1951).

IWING, E. M., Review of geochemistry and its possible application in the Philippines, Philippine Geol., v. 5, no. 2, pp. 47-79, 1951.

KAWANO, YOSHINORI, Natural glasses in Japan, Geol. Sur. Japan, Rep. 134, 32 pp., 1950 (summary in English).

KEBLE, R. A., The Morpington Peninsula, Mem. Geol. Surv. Victoria, no. 17, pp. 84, 1950.

KING, B. C., The wolfram deposits of Singo County, Buganda Province, Uganda, Colonial Geol. and Min. Res., v. 1, no. 4, pp. 303-326, 1950.

LADURNER, JOSEF, Das Quarzgefüge der Muglgneise, Verh. der Austria Geol. Bund., nos. 4-6, pp. 99-118, April, May, June 1949.

LAPLAINE, L., Étude géologique des feuilles Tsiroanomandidy-Soavinandriano, Haut Commissariat, Madagascar, Bur. Géol. Générale, Service des Mines, Tananarive, Madagascar, Travaux 20, 63 pp., 1951.

LAPLAINE, L., Étude géologique des feuilles Moramanga, Brickaville, Haut Commissariat, Madagascar, Bur. Géol. Générale, Service des Mines, Tananarive, Madagascar, Travaux 14, 93 pp., 1950.

LAUTEL, ROBERT, Étude petrographique des formations constitutives des feuilles Ambatomainty (446) et Andranomavokely, Haut Commissariat, Madagascar, Bur. Géol. Générale, Service des Mines, Tananarive, Madagascar, Travaux 11, 27 pp., 1950.

NIGGLI, P., Gesteinschemismus und Magmenlehre, Geol. Rundschau, v. 39, no. 1, pp. 8-32, 1951.

NOE-NYGAARD, ARNE, Hagöngur, a partially sub-glacial volcano in southwestern Vatnagökull, Medd. Dansk Geol. Forening, v. 11, no. 5, pp. 513-521, 1950.

NOE-NYGAARD, ARNE, New traces of extinct thermal activity in Iceland, Medd. Dansk Geol. Forening, v. 11, no. 5, pp. 579-582, 1950.

ORLIAC, M., Étude de l'altérabilité des roches granitiques, Bull. Hist. Nat., Toulouse, v. 85, no. 3-4, pp. 355-362, 1950 (1951).

PILGER, ANDREAS, Die tektonischen Probleme des initialen Magmatismus, Geol. Jb. 1949, Geol. Landesanstalten, Deutschland, pp. 1-30 (1951).

RAO, A. N., Geology and petrology of Kondavidu Hill Range, Guntur District, Madras Presidency, Q. J. Geol. Min. Metal. Soc., India, v. 22, no. 3, pp. 71-88, Sept. 1950.
RAUGIN, E., Observations nouvelles sur le granite de Quérigut (Ariege), Bull. Soc. Hist. Nat., Toulouse, v. 85, no. 3-4, pp. 266-270, 1950 (1951).
RECH-FROLLO, MME., Petrographie du Flysch, Bull. Soc. Hist. Nat., Toulouse, v. 85, no. 3-4, pp. 270-271, 1950 (1951).
REED, J. J., Hornblende andesite rocks from Solander Island, Trans. Proc. R. Soc. New Zealand, v. 79, pt. 1, pp. 119-125, 1951.
ROUBAULT, MARCEL, Quelques remarques sur l'evolution des idées en petrographie un nom trop peu connu J. Durocher, Bull. Hist. Nat., Toulouse, v. 85, no. 3-4, pp. 272-278, 1950 (1951).
SEKI, YOTARO, On the ultrabasic rocks in the Miyamori District, Iwate Prefecture (pt. 3) on serpentinization, J. Geol. Soc. Japan, v. 57, no. 669, pp. 217-224, 1951.
SORENSEN, HENNING, An examination of the plagioclases of some Hekla lavas, Med. Dansk Geol. Forening, v. 11, no. 5, pp. 522-542, 1950.
SUESS, HANS, Gas content and age of tektites, Philippine Geol., v. 5, no. 2, pp. 79-89, 1951.
TERMER, F., Die Tätigkeit des Vulkans Parícutin (Mexico) im Nov. 1949, Geol. Rundschau, v. 39, no. 1, pp. 95-98, 1951.
YODER, H. S., and C. W. CHESTERMAN, Jadeite of San Benito County, California, Calif. Dept. Nat. Res., Div. of Mines, Special Rep. 10-C, 8 pp., Sept. 1951.

BIBLIOGRAPHY: HYDROLOGY

ALLEN, WILLIAM B., Technical investigations of additional ground-water supplies in Rhode Island, J. New England Water Works Assn., v. 65, no. 3, pp. 211-216, Sept. 1951.
ARNOW, THEODORE, The ground-water resources of Columbia County, New York, N. Y. State Dept. Conserv. Bull. G. W. 25, 47 pp., 3 maps, 1951.
ARNOW, THEODORE, The ground-water resources of Fulton County, New York, N. Y. State Dept. Conserv. Bull. G. W. 24, 40 pp., 2 maps, 1951.
AUDEN, J. B., The bearing of geology on multipurpose projects, Presidential address, Sect. 5, Geol. and Geography, 38th Indian Sci. Cong., Bangalore, 45 pp., 1951.
BERDAN, JEAN M., The ground-water resources of Schoharie County, New York, N. Y. State Dept. Conserv. Bull. G. W. 22, 61 pp., 2 maps, 1950.
BLANEY, HARRY F., Consumptive use of water, Proc. Amer. Soc. Civ. Eng., v. 77, 19 pp., Oct. 1951.
BRASHEARS, M. L., Ground-water situation in Japan, Allied Powers, Supreme Command, Natural Resources Sect. Prelim. Study 51, 40 pp., May 1951.
CHOW, VEN TE, A practical procedure of flood routing, Civ. Eng. and Public Works Rev., v. 46, no. 542, pp. 586-588, Aug. 1951.
COOPER, H. H., JR., and V. T. STRINGFIELD, Ground water in Florida, Florida Geol. Surv., Inf. Circ. no. 3, 6 pp., 4 fig., June 1950.
CRAYA, A., Critical regimes of flows with density stratification, Tellus, v. 3, no. 1, pp. 28-42, Feb. 1951.
EAKIN, T. E., and Others, Contributions to the hydrology of eastern Nevada, Nevada Water Resources Bull. 12, 171 pp., 1951.
EINSTEIN, HANS A., and NICHOLAS L. BARBAROSSA, River channel roughness, Proc. Amer. Soc. Civ. Eng., v. 77, 12 pp., July 1951.
FISK, HAROLD N., Mississippi River Valley geology relation to river regime, Proc. Amer. Soc. Civ. Eng., v. 77, 16 pp., July 1951.
GORON, L., Les systèmes fluvio-glaciaires de la Bièrre-Valloire et leur raccordement aux terrasses rhodaniennes, Rev. Géog. Alpine, v. 39, no. 4, pp. 623-672, 1951.
GRIGGS, R. L., and G. E. HENDRICKSON, Geology and ground-water resources of San Miguel County, New Mexico, N. Mex. Bur. Mines and Min. Resources Ground-Water Rep. 2, 116 pp., 1951.
HURSCH, C. R., Research in forest streamflow relations, U. N. Food and Agric. Org., Div. Forestry and Forest Products, Unasylva, v. 5, no. 1, pp. 3-9, January-March 1951.
JARKE, JOACHIM, Die Sedimentation in den schleswig-holsteinischen Förden, Schriften, Naturwiss. Ver., Kiel, v. 25, pp. 204-210, 1951.
KING, RALPH E., Stage predictions for flood-control operations, Proc. Amer. Soc. Civ. Eng., v. 77, 9 pp., July 1951.
LANGBEIN, W. B., and Others, Hydrology of stock-water reservoirs in Arizona, U. S. Geol. Surv. Circ. 110, 18 pp., March 1951.
LUSCZYNSKI, NORBERT J., and ARTHUR H. JOHNSON, The water table in Long Island, N. Y. in January 1951, N. Y. State Dept. Conserv. Bull. G. W. 27, 28 pp., 1951.
LUSK, TRACY WALLACE, Ground-water investigations along Bogue Phalia between Symonds and Malvina, Bolivar County, Mississippi State Geol. Surv. Bull. 72, 19 pp., 1951.

MACKERETH, J. H., A colorimetric method for routine estimation of calcium in natural waters, Analyst, v. 76, no. 905, pp. 482-484, August 1951.
MacKICHAN, KENNETH A., Estimated use of water in the United States, 1950, U. S. Geol. Surv. Circ. 115, 13 pp., May 1951.
MITCHELL, PETER B., Reservoir site investigation and economics, J. Inst. Water Eng., v. 5, no. 5, pp. 445-481, August 1951.
NASU, NORIYUKI, Interpretation of sedimentation phenomena in terms of fluid dynamics, J. Geol. Soc. Japan, v. 57, no. 671, pp. 367-368, August 1951.
NICHOLSON, H. H., Ground-water control in reclaimed marshland, World Crops, v. 3, no. 7, pp. 251-254, July 1951.
PARSHALL, RALPH L., Model and prototype studies of sand traps, Proc. Amer. Soc. Civ. Eng., v. 77, 9 pp., May 1951.
PEARSALL, W. H., Fresh-water biological research and water supply, J. Inst. Water Eng., v. 5, no. 5, pp. 482-484, August 1951.
RICH, L. R., Consumptive use of water by forest and range vegetation, Proc. Amer. Soc. Civ. Eng., v. 77, 14 pp., October 1951.
ROSE, H. E., The analysis of water by the assessment of turbidity, J. Inst. Water Eng., v. 5, no. 5, pp. 521-545, August 1951.
SCHEGA, REYNALDO, Rectification of the Papalaapan River in Mexico, Proc. Amer. Soc. Civ. Eng., v. 77, 13 pp., May 1951.
SHINGLER, DON G., High water on the Kansas River, Mil. Eng., v. 43, no. 295, pp. 322-326, 1951.
SKIDMORE, H. J., The Mississippi Basin model, Mil. Eng., v. 43, no. 295, pp. 347-350, 1951.
SUMMERVILLE, W. A. T., Water erosion: development of the present approach to the problem, Research, London, v. 3, no. 12, pp. 547-550, December 1950.
TAKUJIRO, TAKASAKI, and HACHIRO SASAKI, A study on electrical measurement of percolating velocity of water through sand-bed, Tech. Rep. Tohôku Univ., Japan, v. 15, no. 2, pp. 26-44, 1951.
THOMAS, HAROLD E., The conservation of ground water; a survey of the present ground-water situation in the United States, McGraw-Hill, 327 pp., 1951.
THORNTHWAITE, C. W., The water balance in tropical climates, Bull. Amer. Met. Soc., v. 32, no. 5, pp. 166-173, May 1951.
VAN TUYL, D. W., Ground water for air conditioning at Pittsburgh, Pennsylvania, Dept. Internal Affairs, Top. Geol. Surv. Bull. W10, 32 pp., 1951.
VEYRET, PAUL, La neige au Canada, Rev. Géog. Alpine, v. 39, pp. 533-570, 1951.
WESTERMANN, J. H., The water bore of Oranjestad 1942-1943, and its implication as to the geology and geohydrology of the island of Aruba (Netherlands West Indies), Kon. Ned. Akad. Wetenschappen, Proc., v. 54, no. 2, Ser. B, pp. 140-159, 1951.

BIBLIOGRAPHY: TECTONOPHYSICS

AHRENS, W., and H. KARRENBERG, Stand der stratigraphischen und tektonischen Erforschung der niederrheinischen Braunkohlenformation (Geol. rheinischen Braunkohle 2), Geol. Jb. 1949, Hannover, v. 65, pp. 71-80, 1951.
ALVAREZ, MANUEL, JR., Unidades tectónicas de la República Mexicana, Bol. Soc. Geol. Mexicana, v. 14, pp. 1-22, 1949.
ANDREE, KARL, Geologische Konsequenzen einer Erdentstehung auf kalten Wege, Geol. Rundschau, v. 39, no. 1, pp. 147-149, 1951.
AZHAGIREI, G. D., Some new ways of the development of the structural geology, Izv. Akad. Nauk. SSSR, ser. geol., no. 3, pp. 94-102, 1950.
BARTH, TOM. F. W., The feldspar geologic thermometers, Neues Jb., v. 82, no. 1/2, pp. 143-154, 1951.
BERTHELSEN, ASGER, A Pre-Cambrian dome structure at Tovqussaq, West Greenland, Med. Dansk. Geol. Förening, v. 11, no. 5, pp. 558-572, 1951.
BLUMENTHAL, M. M., Eine Übersicht über die tektonischen Fenster der Betischen Cordilleren Inst. Geol. Min., España, v. 1, Libro Jubilar, pp. 237-314, 1950.
BORDEL, PIERRE, Le dôme permien de Barrol et son auréole de terrains secondaires, Bull. France Service Carte Géol. France, no. 28, v. 48, pp. 51-90, 1950.
CELESTE, RAIMUNDO, Reconocimiento geotectónico en las inmediaciones de Salto Grande (Entre Ríos), Meteoros, v. 1, no. 2-3, pp. 183-188, 1951 (summary in English).
CLARK, R. H., and D. B. McINTYRE, A macroscopic method of fabric analysis, Amer. J. Sci., v. 249, pp. 755-768, 1951.
CORNELIUS, HANS PETER, Geologie der Err-Julier-Gruppe, Gebirgsbau, Beitrage Geol., Karte Schweiz, N. F. 70, pt. 2, pp. 1-264, 1950.
EARDLEY, A. J., Structural geology of North America, Harper and Bros., New York, 1951.
GERTH, H., Die Fortschritte der geologischen Forschung im Kordillerengebiet Südamerikas während und nach dem zweiten Weltkrieg, Geol. Rundschau, v. 39, no. 1, pp. 255-273, 1951.

GERTH, H., Antillen-Molukken, zwei Inselbogen, ein Vergleich des geologischen Baues und der Schweranomalie, Geol. Rundschau, v. 39, no. 1, pp. 273-284, 1951.

GLENNIE, E. A., The Cuddapah Basin in India and crustal warping, Mon. Not. R. Astr. Soc., London, v. 6, no. 3, pp. 168-176, 1951.

HEWITT, D. F., Geology of Shead ownship, Larder Lake Area, Ont. Dept. Mines, v. 58, pt. 6, pp. 1-43, 1951.

JEWETT, JOHN MARK, Geologic structures in Kansas, Geol. Surv. Kansas, Bull. 90, pp. 105-172, 1951.

KHAIN, V. E., On the interrupted cause of the tectonic processes, Izv. Akad. Nauk. SSSR, ser. geol. no. 6, pp. 26-44, 1950.

KOCH, E., Zur Tektonik des Grabens der mittleren Elz (Mittelschwarzwald), Geol. Rundschau, v. 39, no. 1, p. 143, 1951.

KOROVIN, M. K., Geotektonic principle and its importance for stratigraphy and geologic chronology. Izv. Akad. Nauk. SSSR, ser. geol., no. 3, pp. 74-88, 1950.

KVALE, ANDERS, Geology of the area between the Finse district and the Berger arcs, Proc. Geologists' Assn., v. 62, pt. 3, pp. 214-223, 1951.

LENGYEL, ENDRE, Inclusions des andésites des monts de la boucle du Danube et leur signification magma tectonique, Bull. Hungarian Geol. Soc., v. 81, no. 4-6, pp. 119-130, 1951 (in Hungarian with summary in French).

MATHIEU, M. GILBERT, Contribution à l'étude de monts Troglodytes dans l'extrême Sud-Tunisien, Géologie regionale des environs de Matmata Medenine et Foum-Tatahouine, An. Mines and Géol., Tunis, no. 4, ser. 1, 82 pp., 1949.

MATHIEU, M. GILBERT, Des relations structurales entre les Mauges et la Gâtine, Bull. France Service Carte Géol. France, no. 229, v. 48, pp. 91-114, 1950.

McLEARN, F. H., and E. D. KINDLE, Geology of northeastern British Columbia, Geol. Surv. Canada, Mem. 259, pp. 1-236, 1950.

MICHELAU, P., Kleintektonische Fragen im Ruhrkarbon, Geol. Rundschau, v. 39, no. 1, pp. 139-141, 1951.

MOORE, A. J. W., and W. J. McG. TEGART, Rupture of oxide films during repeated sliding, Australian J. Sci. Res., ser. A, v. 4, no. 2, pp. 181-184, 1951.

MORTELMANS, G., Stratigraphie et tectonique des monts Kibara dans la région Mitwaba-Kina, Bull. Soc. Belge, Géol. Pal. Hydrol., v. 59, pp. 359-399, 1950.

MURAWSKI, HANS, Zusammenhänge zwischen Basaltvulkanismus und Tektonik in Niedersachsen, Geol. Rundschau, v. 39, no. 1, pp. 114-119, 1951.

NALIVKIN, V. D., Gently sloping overthrusts in the surroundings of Chusovoi City, Izv. Akad. Nauk., SSSR, ser. geol. no. 4, pp. 154-158, 1950.

NYE, J. F., The flow of glaciers and ice-sheets as a problem in plasticity, Proc. R. Soc., A, v. 207, pp. 554-572, 1951 [abstr. in Phys. Abstr., v. 54, no. 645, p. 858, 1951].

OSBORNE, G. D., The structural evolution of the Hunter-Manning-Myall Province, R. Soc. New South Wales, Monograph 1, 80 pp., 1950.

PILGER, ANDREAS, Eine spezial Aufnahme von Klüfter in einem Flöz des Ruhrgebietes, Geol. Jb., v. 66, pp. 119-140, 1951.

PILGER, ANDREAS, Klüfte und Schlechten in Ruhrkarbon und ihre Darstellung im Kleinriss, Geol. Rundschau, v. 39, no. 1, pp. 136-139, 1951.

RICHTER-BERNBURG, G., Zwei Beiträge zu Fazies, Tektonik und Kupferführung des Zechsteins: I, Waldeck; II, Nordsudeten, Geol. Jb. 1949, Hannover, v. 65, pp. 145-212, 1951.

RIEDEL, L., Das Obere Mucronatensenon-Maastricht in Nordwestdeutschland in stratigraphischer und paläogeographischer Hinsicht, Geol. Jb. 1949, Hannover, v. 65, pp. 381-407, 1951.

SANDER, BRUNO, Über einige Innsbrucker Institutsarbeiten seit 1940, Geol. Rundschau, v. 39, no. 1, pp. 122-130, 1951.

SANDER, BRUNO, Contributions to the study of depositional fabrics (English translation by E. Bliss Knopf), Amer. Assn. Pet. Geol., 160 pp., 1951.

SCHMIDT, WILHELM F., Zur Tektonik des nördlichen Hegaus, Geol. Rundschau, v. 39, no. 1, pp. 143-147, 1951.

SCHÖNENBERG, R., Initialer Magmatismus und Tektonik in Ostthüringen, Geol. Rundschau, v. 39, no. 1, pp. 119-121, 1951.

SCHÖNENBERG, R., Stratigraphie, tektonik und geosynklinales Magmatismus der altesten Oberdevonzeit am Bergaer Sattel (Ostthüringen), Geol. Jb., v. 66, pp. 15-64, 1951.

SEIBOLD, EUGEN, Die Osthälfte des Schwäbischen Lineaments, Geol. Rundschau, v. 39, no. 1, pp. 141-142, 1951.

SOLONENKO, V. P., Problems of the tectonics of the Pre-Cambrian foundation in the folded zone, Izv. Akad. Nauk., SSSR, ser. geol., no. 4, pp. 147-152, 1950.

SUTTON, JOHN, and JANET WATSON, The Pre-Torridonian metamorphis history of the Lock Torridon and Scourie areas in the North-West Highlands, and its bearing on the chronological classification of the Lewison, Q. J. Geol. Soc. London, no. 423, pp. 241-307, 1951.

NOTES AND PERSONALIA

NOTES

Subcommittee Y10.2 (formerly Z10.2), Letter Symbols for Hydraulics, of the American Standards Association--This Committee has recently been reconstituted with the object of reviewing and revising the 1942 Standards on Letter Symbols for Hydraulics. The Committee will appreciate receiving comments from interested persons concerning the 1942 Standards and any suggested additions or modifications thereof. It has been tentatively decided to consider the field of hydraulics as being concerned with all phases of the motion of liquids. An attempt will be made to include symbols in the field of hydrology and water-hammer. Suggestions and comments should be directed to the Chairman, J. M. Robertson, P. O. Box 30, State College, Pennsylvania.

High-elevation research laboratories in India--Sites have been selected in northern India for the establishment of laboratories to undertake snow-survey and other high-altitude research work at elevations of 12,500, 14,000, 15,000, and 18,000 ft. The highest is situated near Mana Pass, 26 miles north of Badrinath, and the laboratory, when built, will probably be the highest in the world. The site selection is one of the products of the survey in 1947 led by James E. Church, on the invitation of the Indian government, and bears especially on the forecasting of water supplies in northern India based on the results of snow surveys.

Establishment of Foundation of Soil Science at the University of California--The M. Theodore Kearney Foundation of Soil Science has been established at the University of California in Berkeley, endowed with $2,268,000, the proceeds of the bequest of M. Theodore Kearney, prominent rancher in the Fresno, California, area in the latter part of the last century. The Foundation will be devoted to the advancement of soil science, including soil-plant-water relations, particularly with regard to arid and semi-arid regions.

Reorganization of climatological and hydrologic work of the U. S. Weather Bureau--The Division of Climatological and Hydrologic Services of the Weather Bureau, organized in 1946, has been reorganized as the Climatological Services Division under the direction of W. F. McDonald (who continues as Assistant Chief of the Bureau for Administration) and the Hydrologic Services Division under the direction of William E. Hiatt. This reorganization is in recognition of the increasing importance of these fields.

Conference on Auroral Physics at the University of Western Ontario--A Conference on Auroral Physics was held at the University of Western Ontario, London, Ontario, July 23-26, 1951. More than 120 were in attendance, representing nine countries. About 20 scientific papers were presented. It is anticipated that these will be published in due course. Interested persons should write to either of the two sponsors, the University or the Air Force Cambridge Research Center, 230 Albany Street, Cambridge 39, Massachusetts.

Curriculum in geophysical engineering accredited at St. Louis University--The first curriculum in geophysical engineering has been accredited by the Engineers' Council for Professional Development in the Institute of Technology of St. Louis University.

Journal of Geological Education--A Journal of Geological Education has been established by the Association of Geology Teachers. It is the plan that this shall be published semi-annually. Volume 1, No. 1, was released in the spring of 1951.

Meeting of Eastern Snow Conference--The Eastern Snow Conference will hold its annual meeting at the Sheraton Hotel, Springfield, Mass., February 14-15, 1952. Interested persons should write to the Secretary of the Conference, Dean B. Bogart, P. O. Box 948, Albany 1, N. Y.

PERSONALIA

Christian T. Elvey, Senior Scientist and Deputy Head of the Research Department of the Naval Ordnance Test Station at China Lake, California, has been designated Director of the Geophysical Institute of the University of Alaska. He will assume his new duties on January 1, 1952.

Gordon M. Fair, Gordon McKay Professor of Sanitary Engineering, and Abbott and James Lawrence Professor of Engineering, Harvard University, has been awarded an honorary degree of Doctor of Engineering by the Technical Institute of Stuttgart, Germany.

Robert Y. Grant, Chief of the Mining and Geology Division, Natural Resources Section, GHQ, SCAP, in Japan has resigned and is returning to the United States.

Gail A. Hathaway, Special Assistant to the Chief of Engineers, U. S. Army, was recently awarded the degree of Doctor of Engineering by Drexel Institute of Technology.

Richard A. Hertzler, formerly Chief of Research on Wood Utilization of the Southeastern Forest Experiment Station of the U. S. Forest Service, has taken up duties as Flood-Control Survey Officer in the Office of the Secretary, U. S. Department of Agriculture.

Edward N. Munns, Chief of the Division of Forest Influences of the U. S. Forest Service, retired September 1, 1951, and is now living at Concord, California. Harold G. Wilm has been named as his successor.

Malcolm Pirnie, Consulting Engineer in New York, has been named a member of the newly established Harvard Foundation Council.

Otto Schneider has taken up duties as Asesor Técnico del Director General, Servicio Meteorológico Nacional of Argentina. He was formerly the Chief of the Geophysical Division.

Frank G. Snyder of the Department of Geology, University of Tennessee, has taken up duties on the technical staff of the St. Joseph Lead Co. and is stationed at Leadwood, Mo.

Charles Volney Averill, Supervising Mining Engineer, California Division of Mines, died August 29, 1950 at the age of 58. He was born in Virginia City, Nevada, and took his baccalaureate degree from the University of California in 1914. His early professional years were devoted to various aspects of mining engineering, and included a two-year tour of duty on mechanical engineering work with the Standard Oil Co. He entered the service of the Division of Mines in 1928, advancing through various positions and becoming Supervising Mining Engineer in 1947. He had been a member of AGU since 1947.

Charles Stuart Bennett, Hydraulic Engineer and Assistant Chief Engineer of the Miami Conservancy District, Ohio, died March 10, 1951 at the age of 59. He was born in Cincinnati, Ohio, and took his baccalaureate degree from Purdue University in 1914. He began his professional career in highway and bridge construction work in Kentucky. In 1917, he entered the service of the Miami Conservancy District, working through the construction phases of that pioneer project, and continued in its operational and maintenance phases until the time of his death. He became a member of AGU in 1939.

Laurie Reid Burgess, Chief, Seismological Operations Section of the U. S. Coast and Geodetic Survey, died in San Francisco, California, August 23, 1951 at the age of 30. He was born in Washington, D. C. He took his baccalaureate degree from William and Mary College in 1942 and secured an engineering degree from New York University in 1943. He served in the Air Force during World War II, rising to the rank of Captain, and was attached to the 19th Tactical Command providing weather data. In 1946, he began his service with the U. S. Coast and Geodetic Survey at Cheltenham Magnetic Observatory, subsequently serving as Observer-in-Charge at the Honolulu Magnetic Observatory where he aided in establishing the seismic sea-wave warning program. In 1949, he took up his duties with the Seismological Operations Section. He had been a member of AGU since 1947.

Daniel Lyman Hazard, former Chief of the Division of Terrestrial Magnetism of the U. S. Coast and Geodetic Survey, died September 21, 1951 at his home at Narragansett, Rhode Island, at the age of 86. He was born at South Kingston, Rhode Island, and, after studying at Brown University, took his baccalaureate degree from Harvard University in 1885. His early professional years were devoted to land-surveying work in Rhode Island and Massachusetts. In 1892, he entered the service of the U. S. Coast and Geodetic Survey, which work he continued in various capacities until his retirement in 1936. He was the author of numerous papers and three books relating to the magnetism of the Earth, on which he was a recognized world authority. He was one of the 47 founding members of the American Geophysical Union. He served as Secretary of the Section of Seismology from 1922 to 1928, and as President of the Section of Terrestrial Magnetism and Electricity from 1928 to 1931.

William Francis Sprengnether, Jr., head of the Sprengnether Instrument Co. in St. Louis, was drowned in the Mississippi River while on vacation with his family on August 30, 1951. He was born in St. Louis, Missouri, in 1909. He took his baccalaureate and master's degrees both from St. Louis University in 1934 and 1936, continued the instrument company founded by his father, and did extensive work in the development of geophysical instruments, especially seismographs and magnetometers. He became a member of AGU in 1945, and, in 1950, brought his company into corporation membership.

SPECIAL ANNOUNCEMENTS

Meeting in Pasadena, Calif., February 8-9, 1952--This meeting, organized by the Regional Committee established early in 1951, will be held in Pasadena, California, with the Sections of Meteorology, Hydrology, and Seismology participating. J. W. Johnson, University of California, Berkeley, is Chairman of the Regional Committee; Vito A. Vanoni, California Institute of Technology, Pasadena, is Chairman of the Committee on Local Arrangements. The program chairmen are as follows: For Meteorology, Morris Neiburger, University of California, Los Angeles; and for Hydrology, H. F. Blaney, 1509 Post Office and Court House Building, Los Angeles. Those interested in the meeting should get in touch with one of these.

The region tentatively established by the Executive Committee in 1949 [see Trans., v. 30, pp. 936-939, Dec. 1949] included California and Hawaii. Suggestions from members indicate that the boundaries should also include Nevada and probably Arizona. Further suggestions from members are requested. However, interest need not be limited by boundaries of regions, and members and others interested, regardless of geographic location, are invited to take part in any meeting. The boundaries are administrative only.

Thirty-Third Annual Meeting, Washington, D. C., May 5-7, 1952--Attention is called to the full notice concerning the Thirty-Third Annual Meeting on page 807 of the October issue of the Transactions. Note that titles and abstracts (not more than 150 words) of papers for the program should be sent in as soon as possible, and not later than March 10, 1952. Section Secretaries reserve the right to close programs filled in advance of that date. With the complete manuscripts, which should be in the office of AGU by April 15, 1952, authors should send advice as to whether the paper is to be considered for publication in the Transactions. Also, send in word concerning special projection equipment. Only a standard slide projector will be provided unless other word is received. Communications should be sent to the appropriate Secretary, listed in the October announcement, or to the office of AGU.

In preparing your paper for presentation, bear in mind that requirements are quite different than for publication. We might borrow the succinct instructions of the Association of Seismology, IUGG, at the Brussels Meeting in the summer of 1951: "Speak slowly, clearly, and briefly; avoid mathematics."

Block bookings have been made at four hotels as follows (they are listed in the decreasing order of the number of rooms booked):

Roger Smith Hotel, Pennsylvania Avenue at 18th Street, Northwest
Willard Hotel, Pennsylvania Avenue at 14th Street, Northwest
Raleigh Hotel, Pennsylvania Avenue at 12th Street, Northwest
Washington Hotel, Pennsylvania Avenue at 15th Street, Northwest

Make your hotel or room reservation early directly with the hotel of your choice. If requesting block-booked space, be sure to cite the AGU meeting.

Meeting in Chicago, September 11-12, 1952--A Mid-West meeting of AGU will be held in Chicago, Illinois, September 11-12, 1952 in connection with the celebration of the Centennial of Engineering. It is anticipated that the Sections of Meteorology and Hydrology, and possibly Tectonophysics and others, will join in this meeting. The headquarters hotel will be the Del Prado, but all scientific seassions will be held on the campus of the University of Chicago. The General Chairman of the Committee arranging the meeting is Horace R. Byers, Department of Meteorology, University of Chicago. Interested persons should get in touch with him.

Index to back Transactions--In order to make the papers in the earlier Transactions more readily available, an index has been prepared for the first 25 years of the Transactions, covering the interval from 1920 to 1944, up to the time that Transactions were issued bimonthly. This is a combined, alphabetical subject and author index, comprising a total of 144 pages, bound in gray paper cover. The price is $4.00.

GEOPHYSICAL RESEARCH CORPORATION

Geophysical Prospecting
Application of Geophysical Methods in the Petroleum Industry

2607 North Boston Place
Tulsa 6, Oklahoma

GULF RESEARCH & DEVELOPMENT COMPANY
GULF OIL CORPORATION

Geophysical and Other Research
Relating to the Petroleum Industry

P. O. Drawer 2038
Pittsburgh 30, Pennsylvania

INSTITUTE OF GEOPHYSICS

UNIVERSITY OF CALIFORNIA

Los Angeles 24, California

RANNEY METHOD WATER SUPPLIES, INC.

Ground Water Exploration and Development

841 Alton Avenue
Columbus 3, Ohio

RUSKA INSTRUMENT CORPORATION

Developers, Designers, and Manufacturers of Instruments for Field and Observatory Use
Magnetic, Geodetic, Seismic, and Meteorological Work

4607 Montrose Boulevard
Houston 6, Texas

SEISMOGRAPH SERVICE CORPORATION

Seismic Exploration Service for
Oil and Gas Structures throughout the World

P. O. Box 1590
Kennedy Building
Tulsa 1, Oklahoma

SPRENGNETHER INSTRUMENT COMPANY

Manufacturer of Seismological and Geophysical Instruments
Instrumental Development and Research

4567 Swan Avenue
St. Louis 10, Missouri